Measuring cosmological parameters

Rupert Croft
McWilliams Center for Cosmology, CMU

Talk plan:

(1) A look at cosmological parameter measurements published over the past 20 years.

(a) How accurate were the quoted error bars?

(b) Ranking techniques by their accuracy

(c) How rapidly does precision increase with time?

(d) Lessons for future measurements of w', f_{NL}, …

(2) Astrometric cosmology

(a) Can we constrain cosmological parameters with direct angular position measurements of quasars?

(b) What will we measure?

(c) Observational uncertainties

(d) How competitive will upcoming satellites be?

>2000 measurements of cosmological parameters have been published since 1990. To be included in this compilation we need

(a) Numerical determination + error bar in abstract
(b) Restricted to 2 journals: ApJ and MNRAS
(c) 13 Parameters: H_0, Ω_M, Ω_Λ, n, σ_8, m_ν, $\Gamma=\Omega h$, $\beta=\Omega^{0.6}/b$, $\eta_8=\sigma_8\Omega^{0.6}$, w_0, q_0, Ω_B, Ω_K

550 measurements

The 550 measurements have been made with many different techniques. These techniques could be broken up into at least 50 categories: e.g. Weak lensing blank field shear, X-ray cluster gas mass fraction, Supernova distance estimate etc..

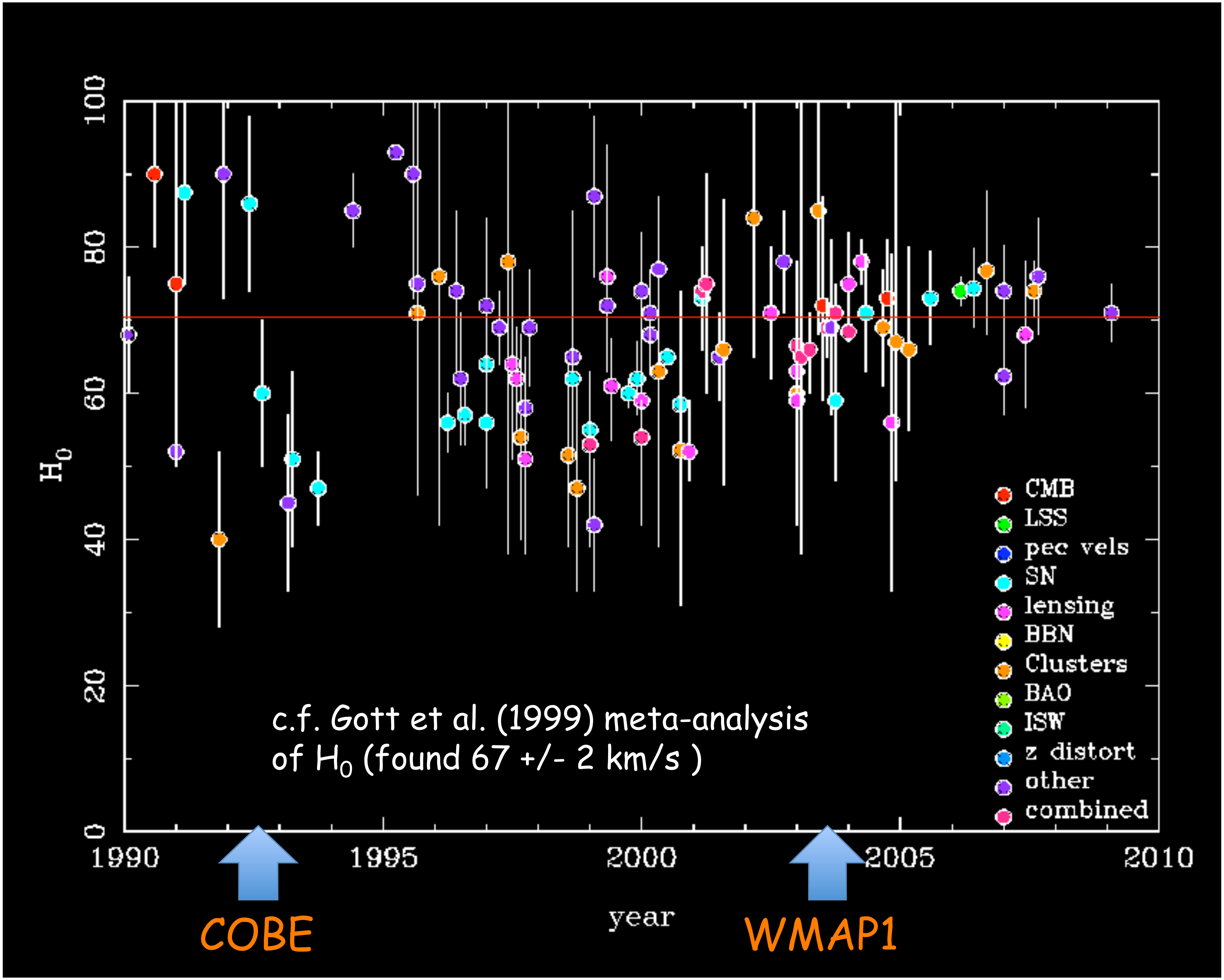
We have consolidated these categories into 11:

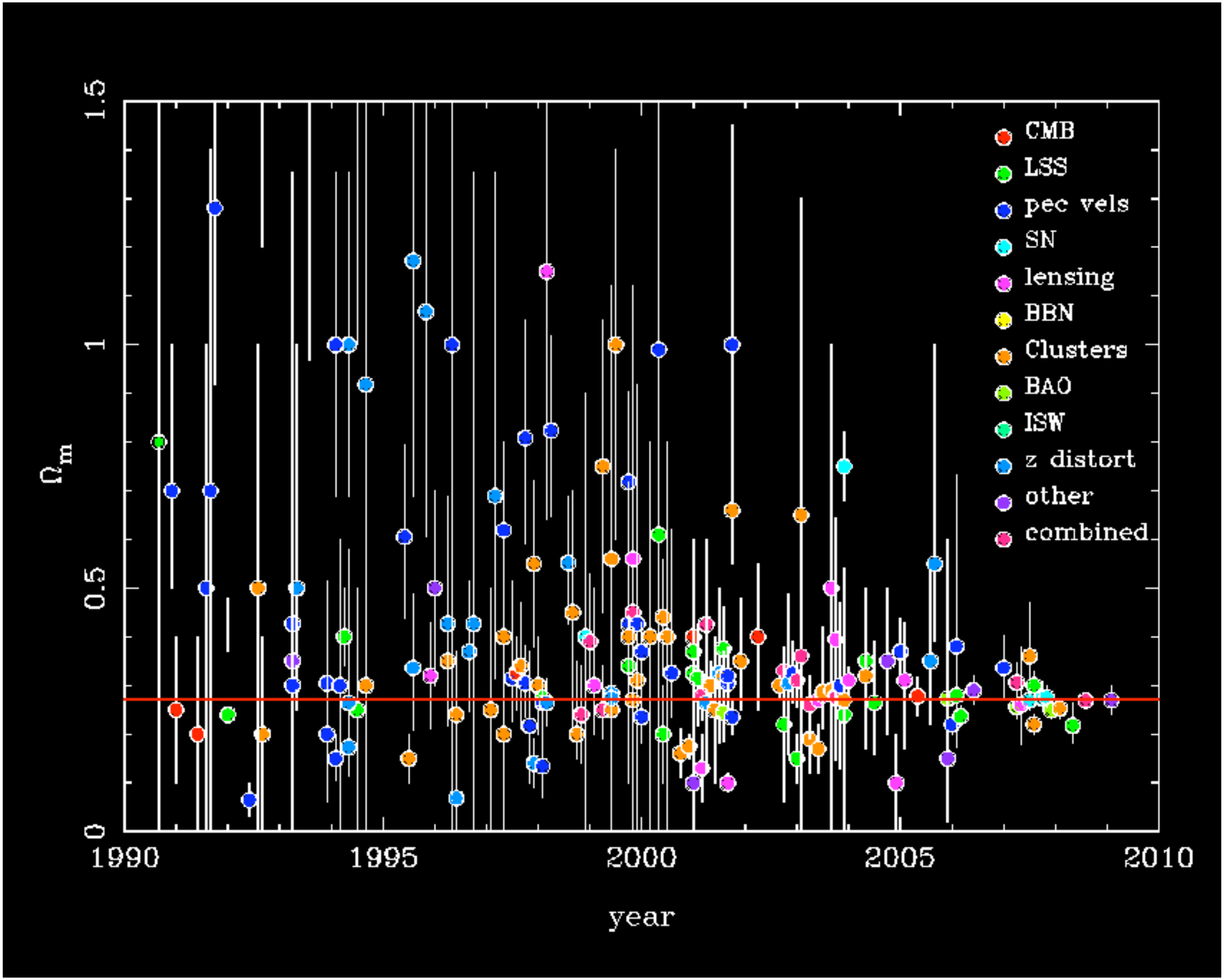
CMB, LSS, Clusters, Pec vels, Lensing, BAO, SN, ISW, redshift distort., “combined methods” and “other”.

To gauge how accurate these past measurements were, we compare them to

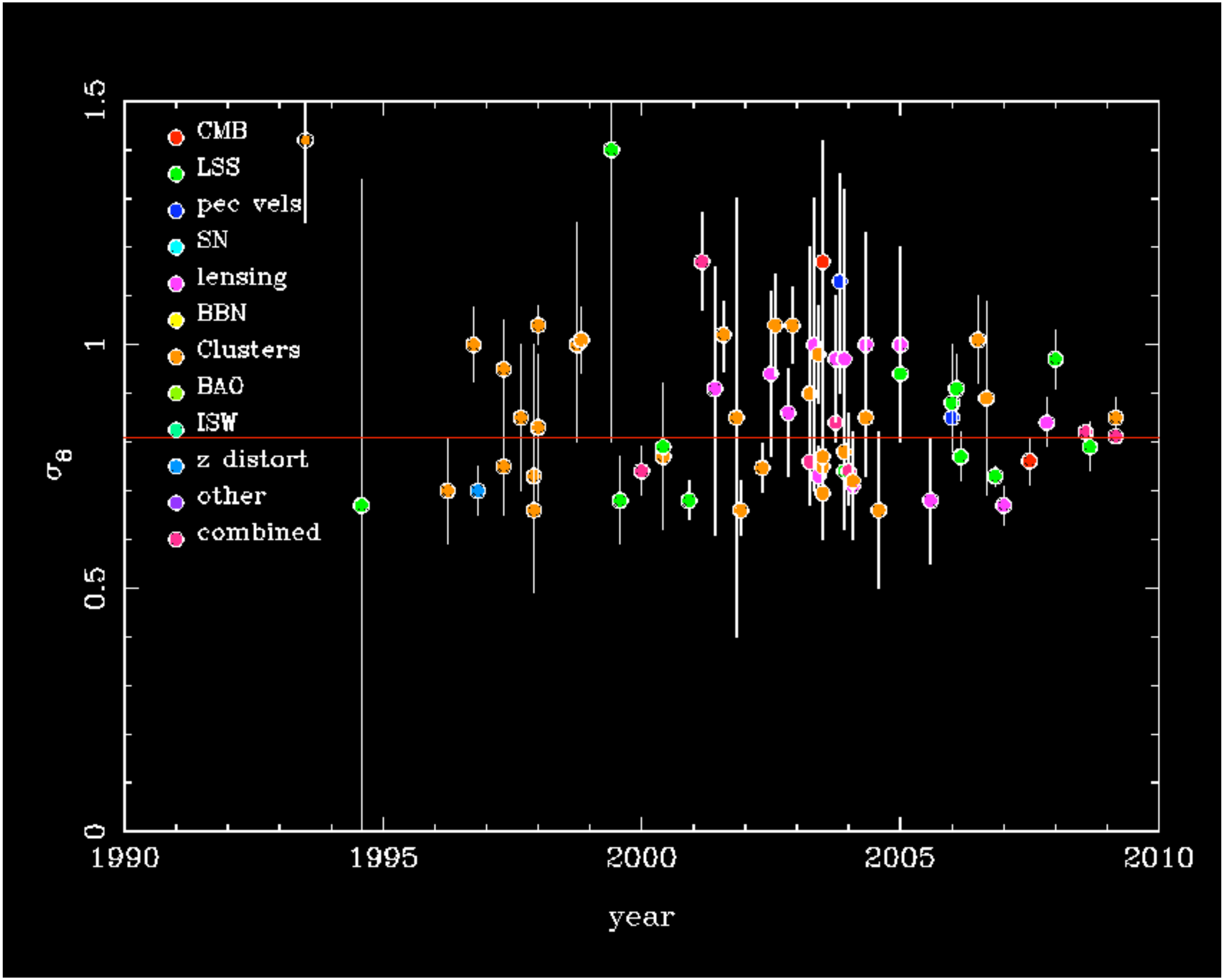
WMAP7 (Komatsu et al 2010)

First some examples of measurements vs year...

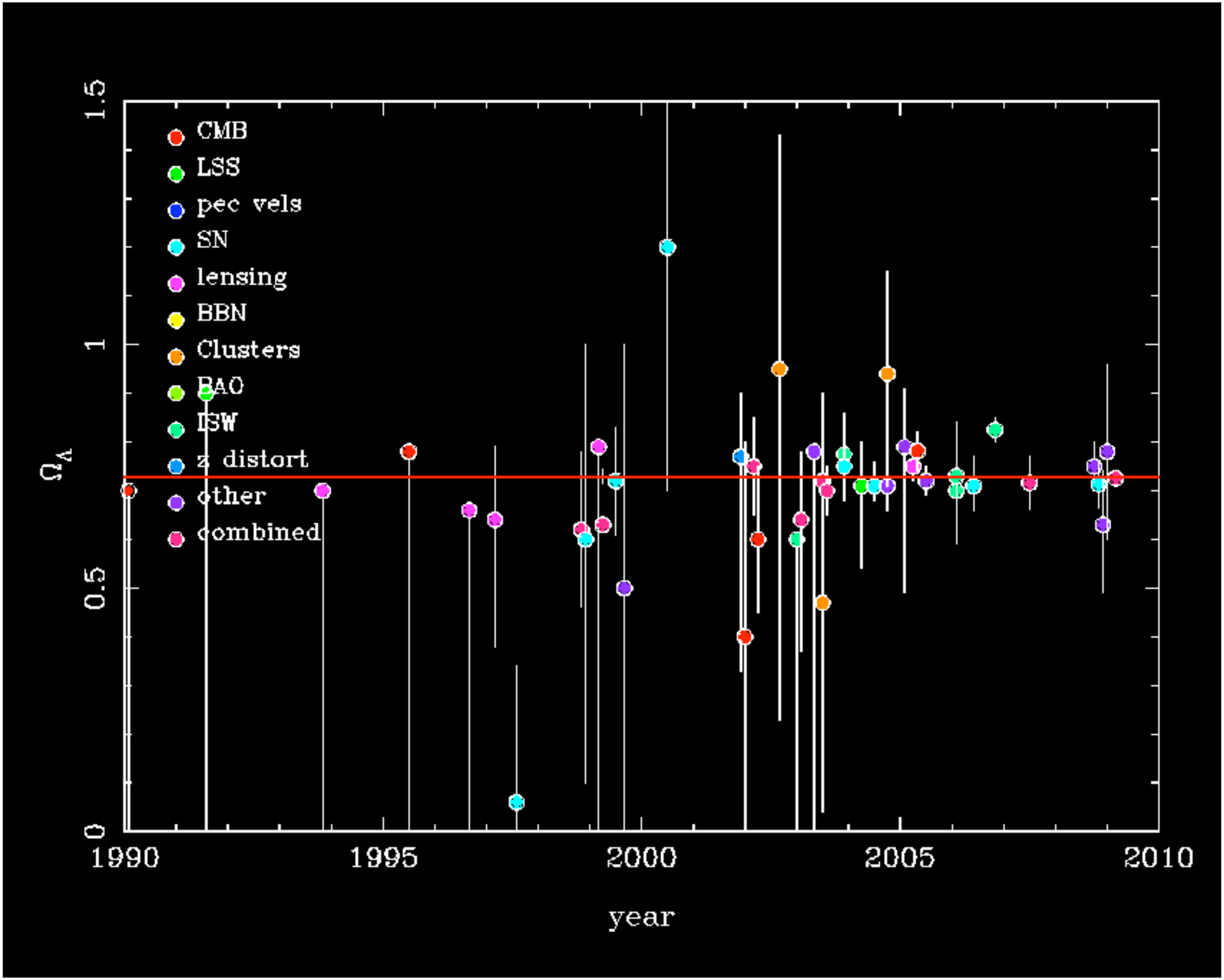

100
80
60
40
20
0
H_0
1990
1995
2000
2005
2010
year
CMB
LSS
pec vels
SN
lensing
BBN
Clusters
BAO
ISW
z distort
other
combined
c.f. Gott et al. (1999) meta-analysis
of H_0 (found 67 +/- 2 km/s)
COBE
WMAP1



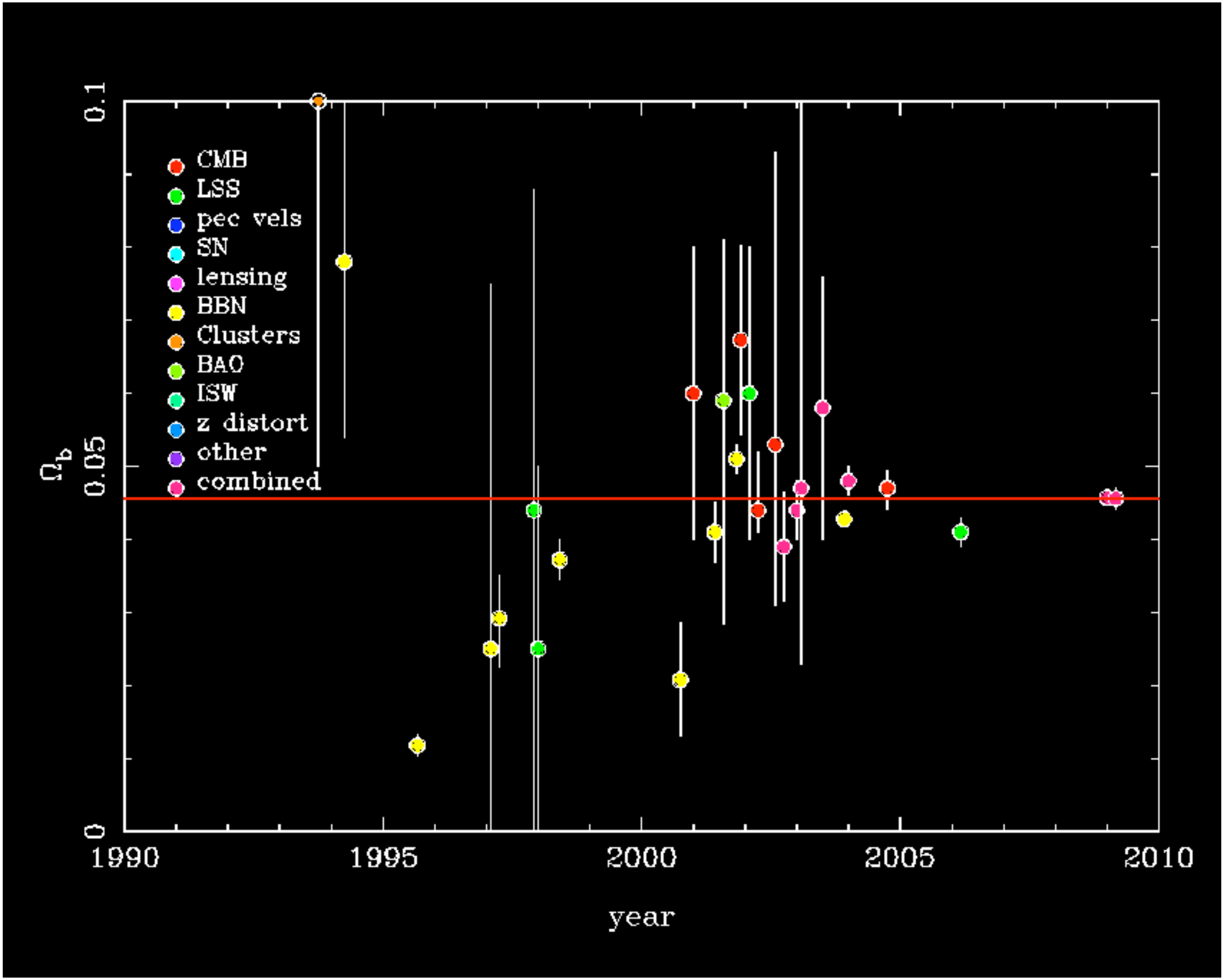
CMB
LSS
pec vels
SN
lensing
BBN
Clusters
BAO
ISW
z distort
other
combined
Ω_m
year
0
0.5
1
1.5
1990
1995
2000
2005
2010



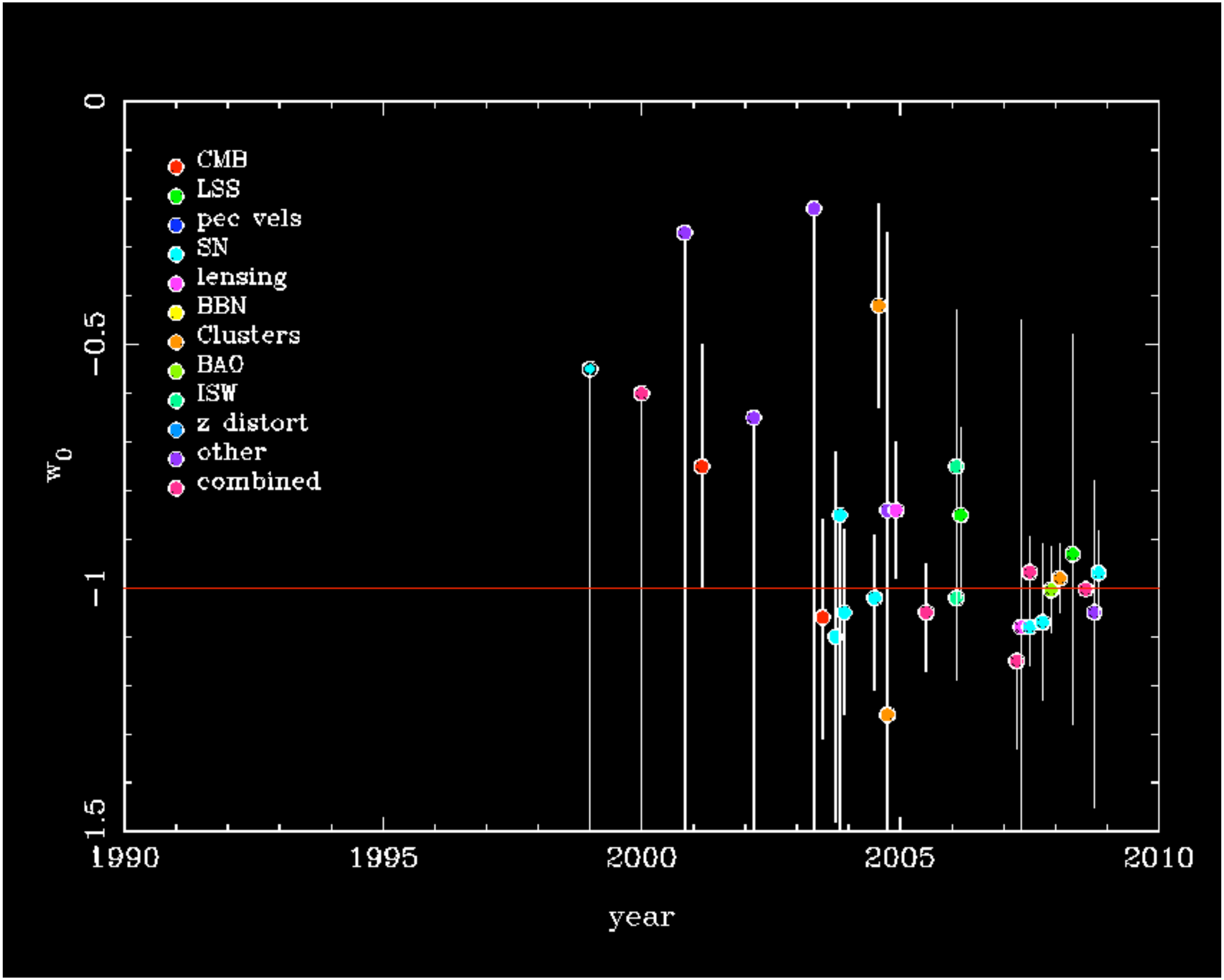
CMB
LSS
pec vels
SN
lensing
BBN
Clusters
BAO
ISW
z distort
other
combined
σ_8
year
0
0.5
1
1.5
1990
1995
2000
2005
2010



CMB
LSS
pec vels
SN
lensing
BBN
Clusters
BAO
ISW
z distort
other
combined
Ω_Λ
1.5
1
0.5
0
1990
1995
2000
2005
2010
year



CMB
LSS
pec vels
SN
lensing
BBN
Clusters
BAO
ISW
z distort
other
combined
Ω_b
0
0.05
0.1
1990
1995
2000
2005
2010
year

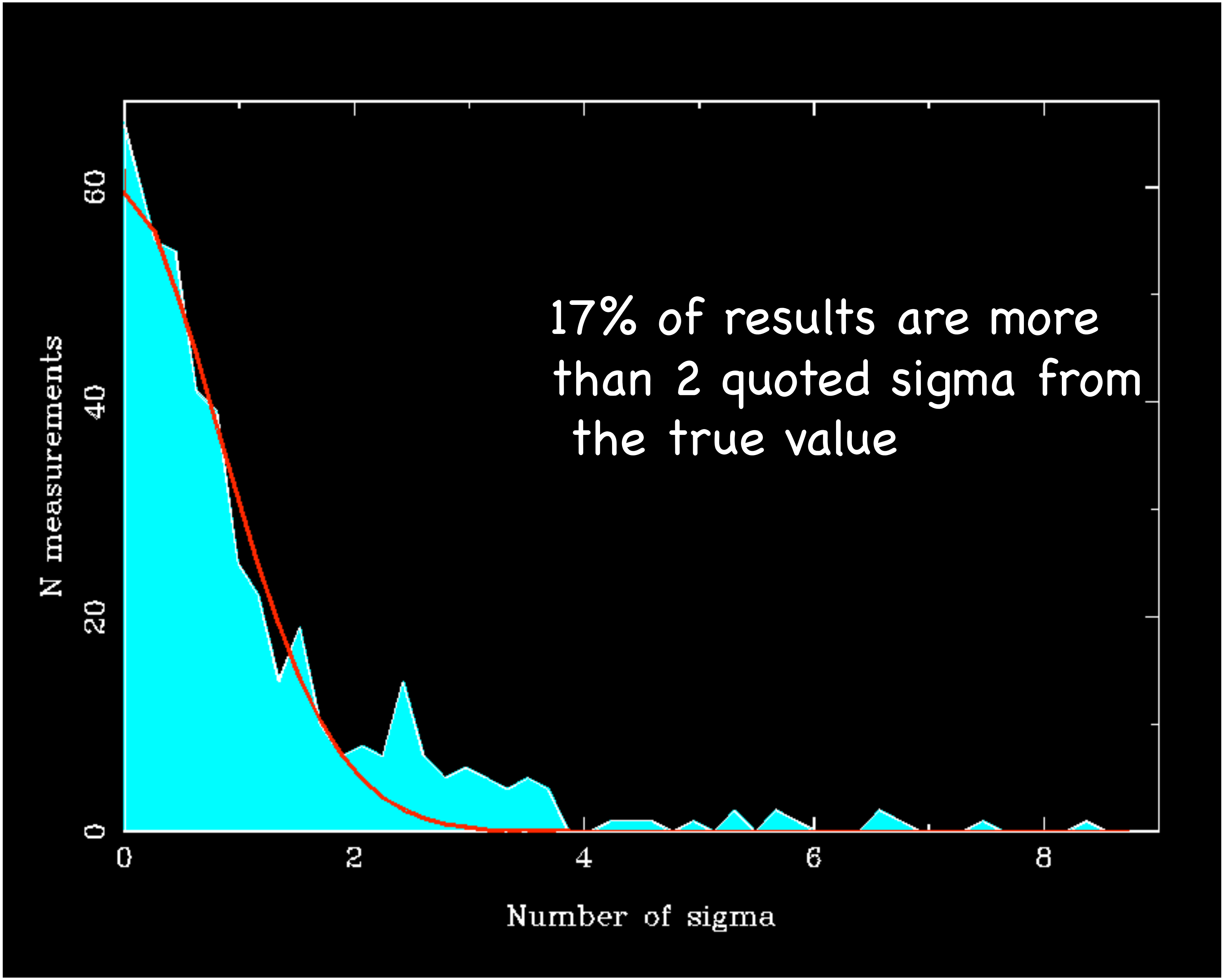


0
-0.5
-1
-1.5
w_0
1990
1995
2000
2005
2010
year
CMB
LSS
pec vels
SN
lensing
BBN
Clusters
BAO
ISW
z distort
other
combined

Overall, how realistic are the error bars
(if we assumed the quoted error bars are Gaussian?)

-Plot a histogram of number of sigmas away
from the “true” (WMAP7+) value:

(is it Gaussian?)

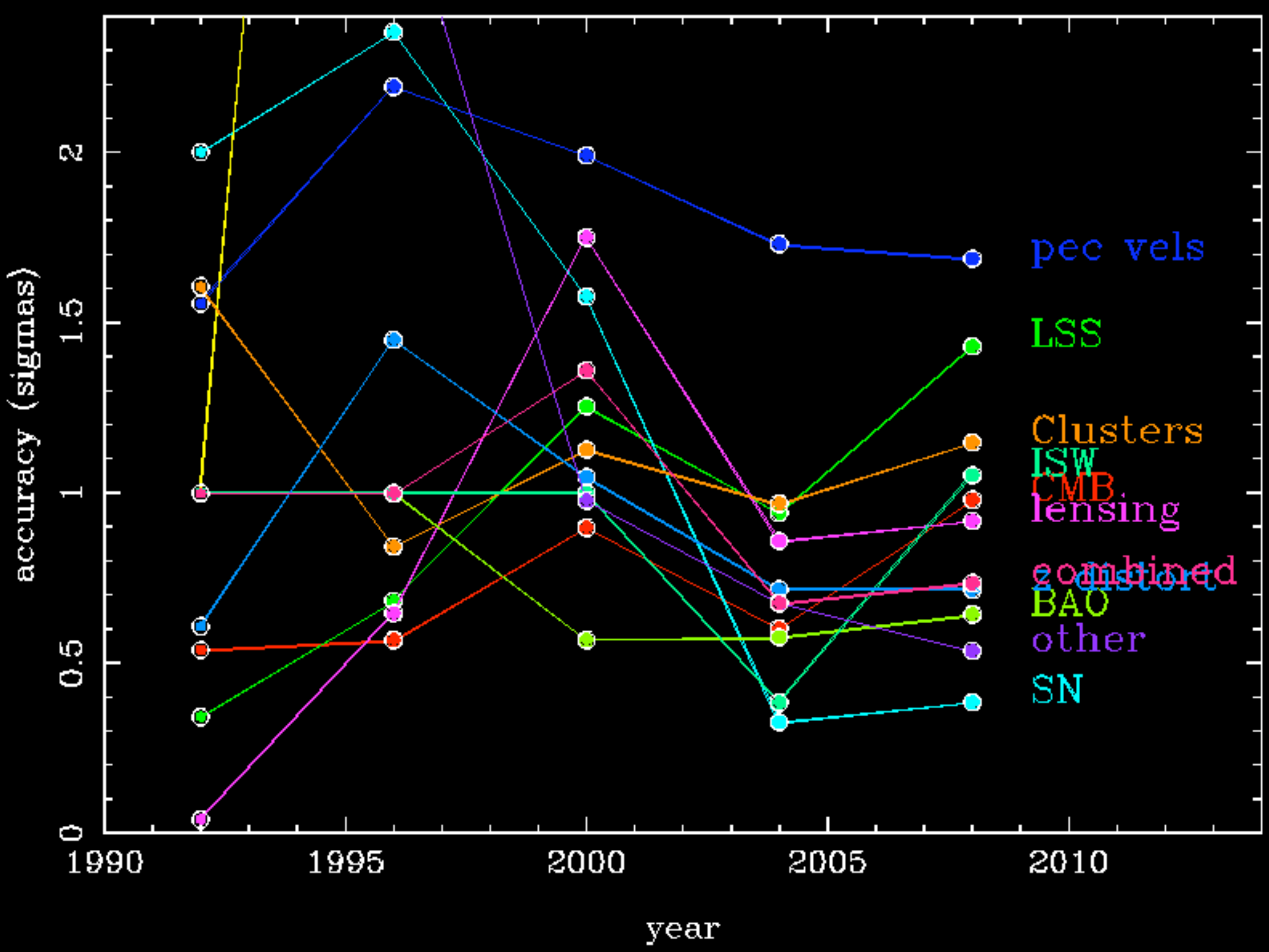

17% of results are more than 2 quoted sigma from the true value
N measurements
Number of sigma
0
20
40
60
0
2
4
6
8

This does however hide a large variation between techniques – we can plot the mean number of sigmas from the true value for each technique.

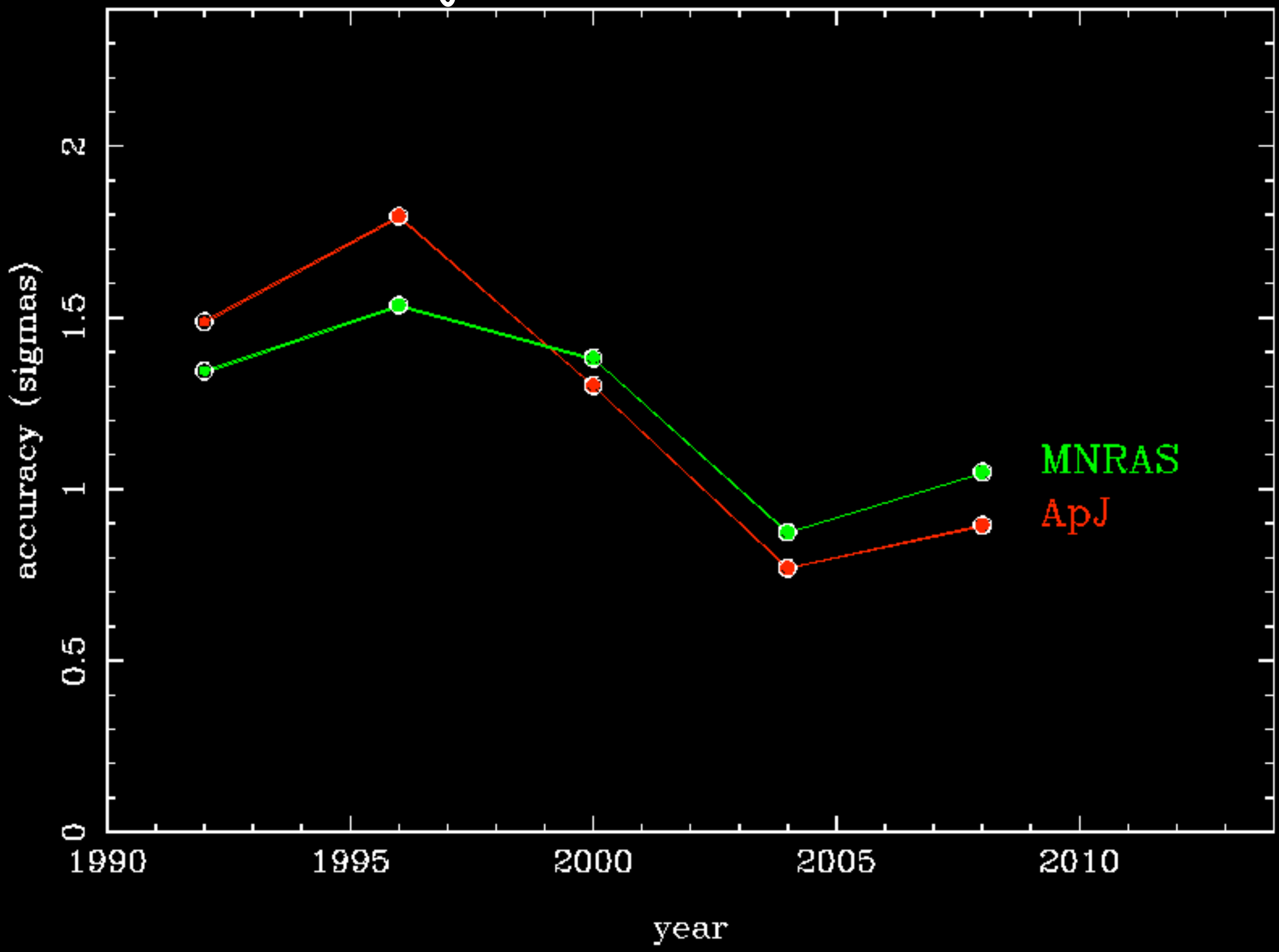
-See which technique (e.g. clusters, SN etc) is the most accurate.

-If the number of sigmas is very low, this could mean that a technique underestimates error bars.

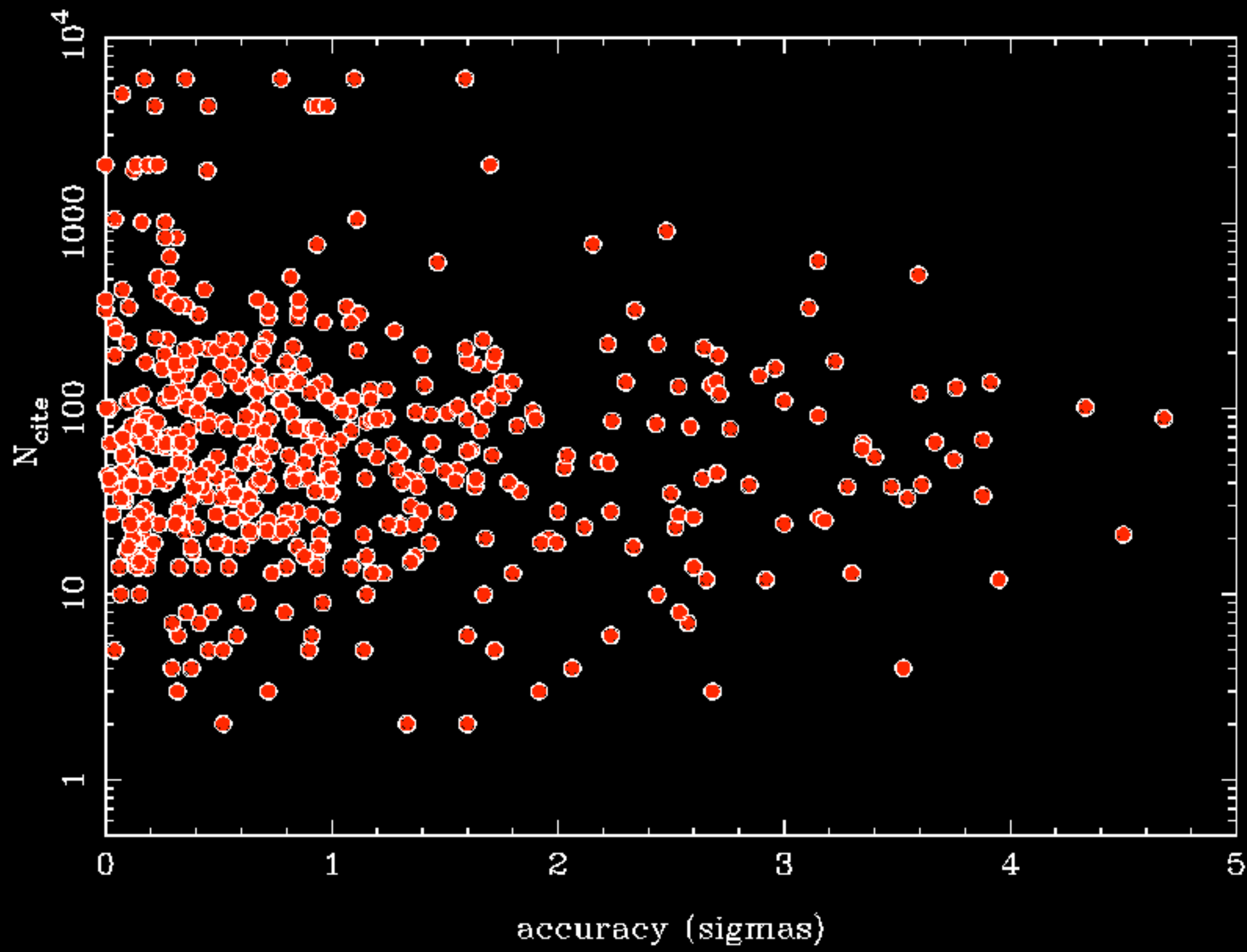
Methods ranked vs year

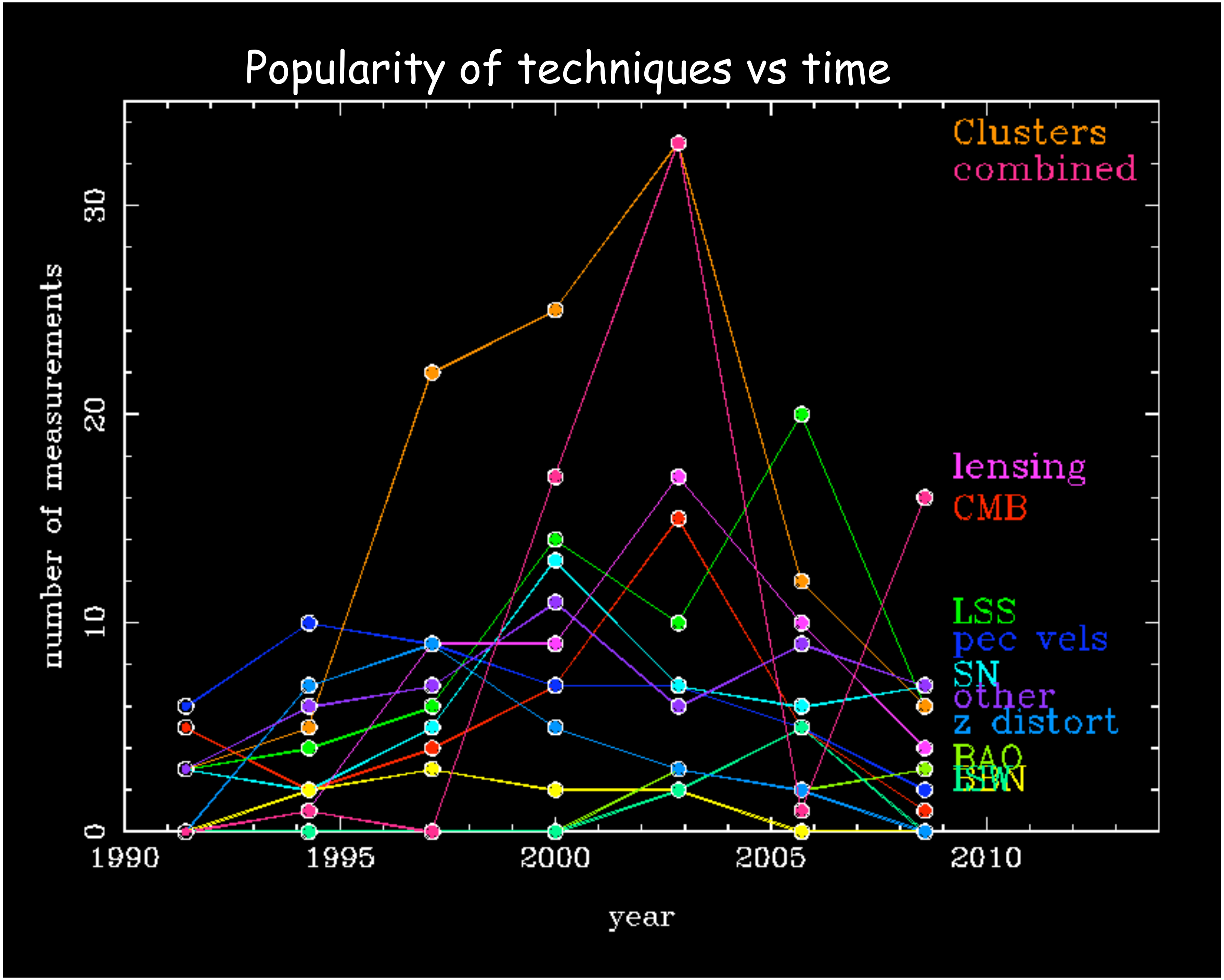


Which journal is most accurate?



Does being more accurate get you more citations?



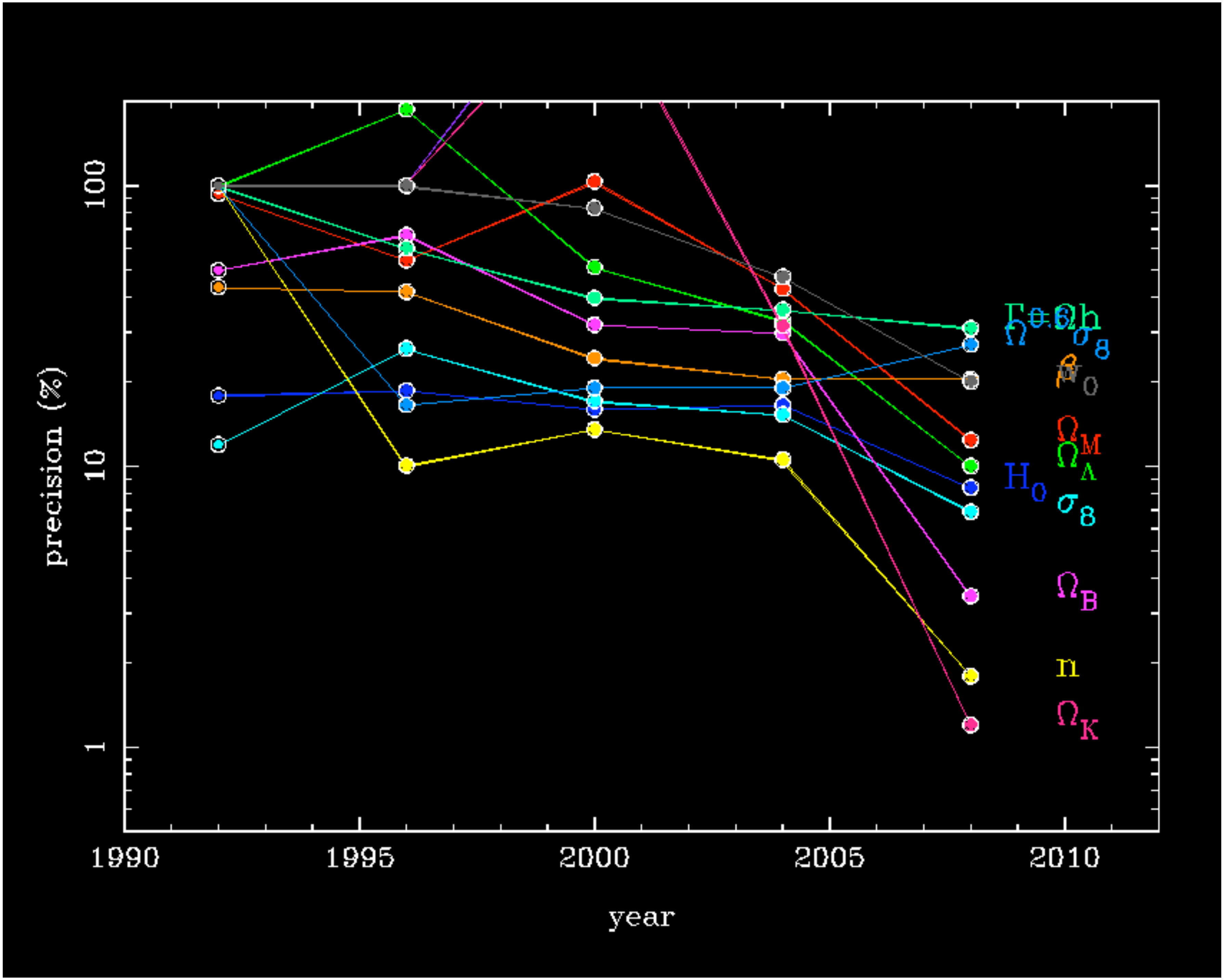


Popularity of techniques vs time
number of measurements
year
0
10
20
30
1990
1995
2000
2005
2010
Clusters
combined
lensing
CMB
LSS
pec vels
SN
other
z distort
BAO

Finally (for the first part of the talk)
we look at how we are approaching precision cosmology…

-which parameters can be measured most precisely? – we plot the mean percentage error bars

-how has this precision improved with time? (e.g. can we use this to tell us how long before we will measure f_{NL} to 1% precision



precision (%)
100
10
1
1990
1995
2000
2005
2010
year
Γ=Ωh
Ω0.6 σ8
β
w0
ΩM
ΩΛ
H0
σ8
ΩB
n
ΩK

Conclusions (for 1st part)

(a) On average, published measurements of Cosmological parameters are quite accurate (but there is a significant non-Gaussian tail)

(b) Peculiar velocities and clusters are the least accurate techniques.

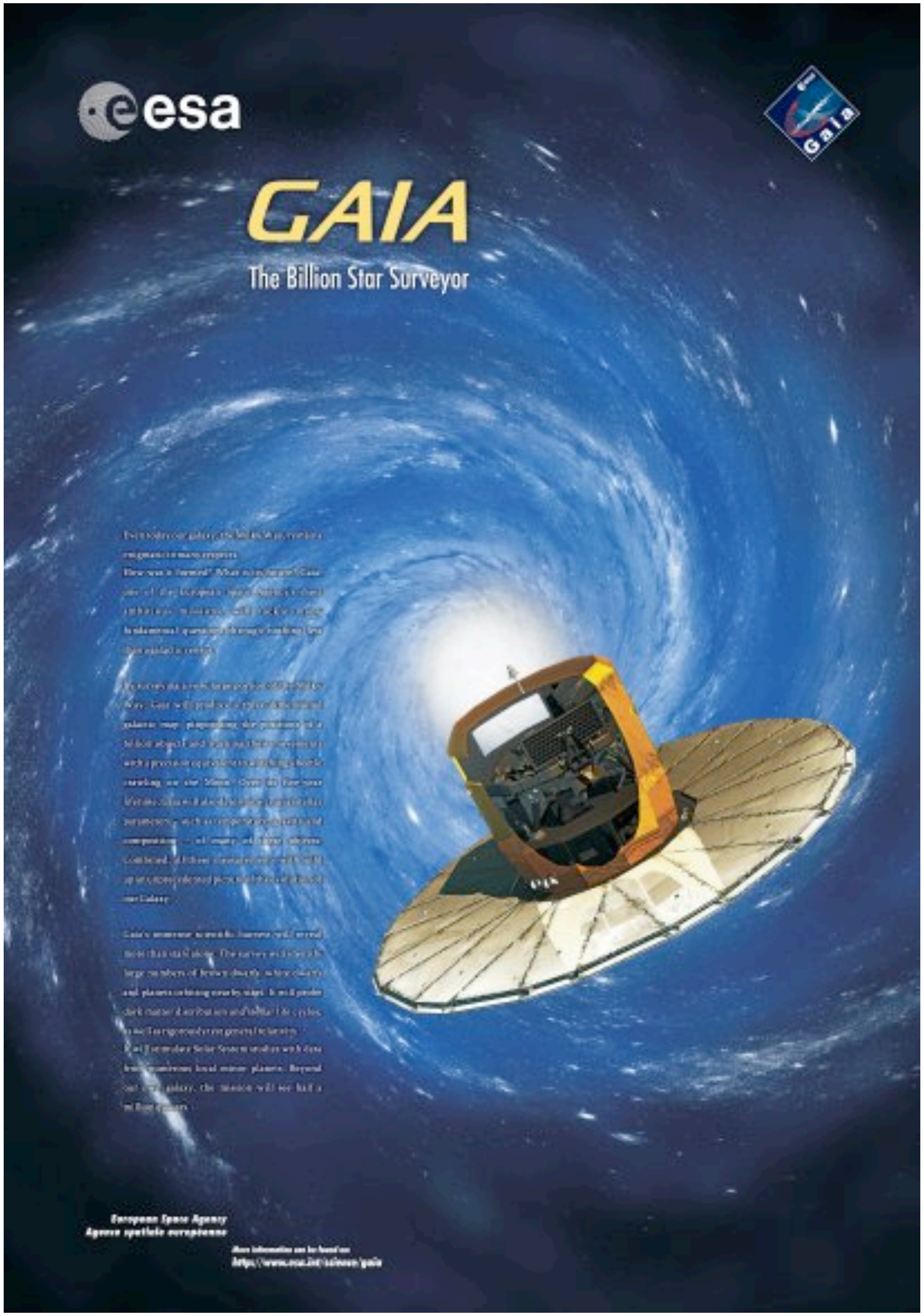
(c) SN and BAO are the most accurate (by a factor of ~3 compared to (b)

(d) On average it takes 14 years for a factor of 10 improvement in measurement precision.

(e) New techniques (e.g. SN, BAO when introduced) can make a big difference – we need more!

Astrometric Cosmology

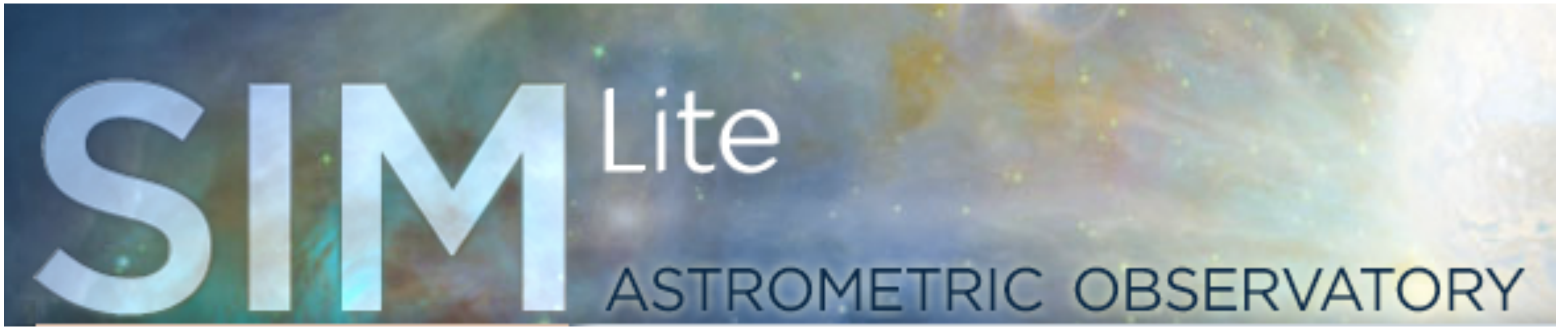
(with Fiona Ding)

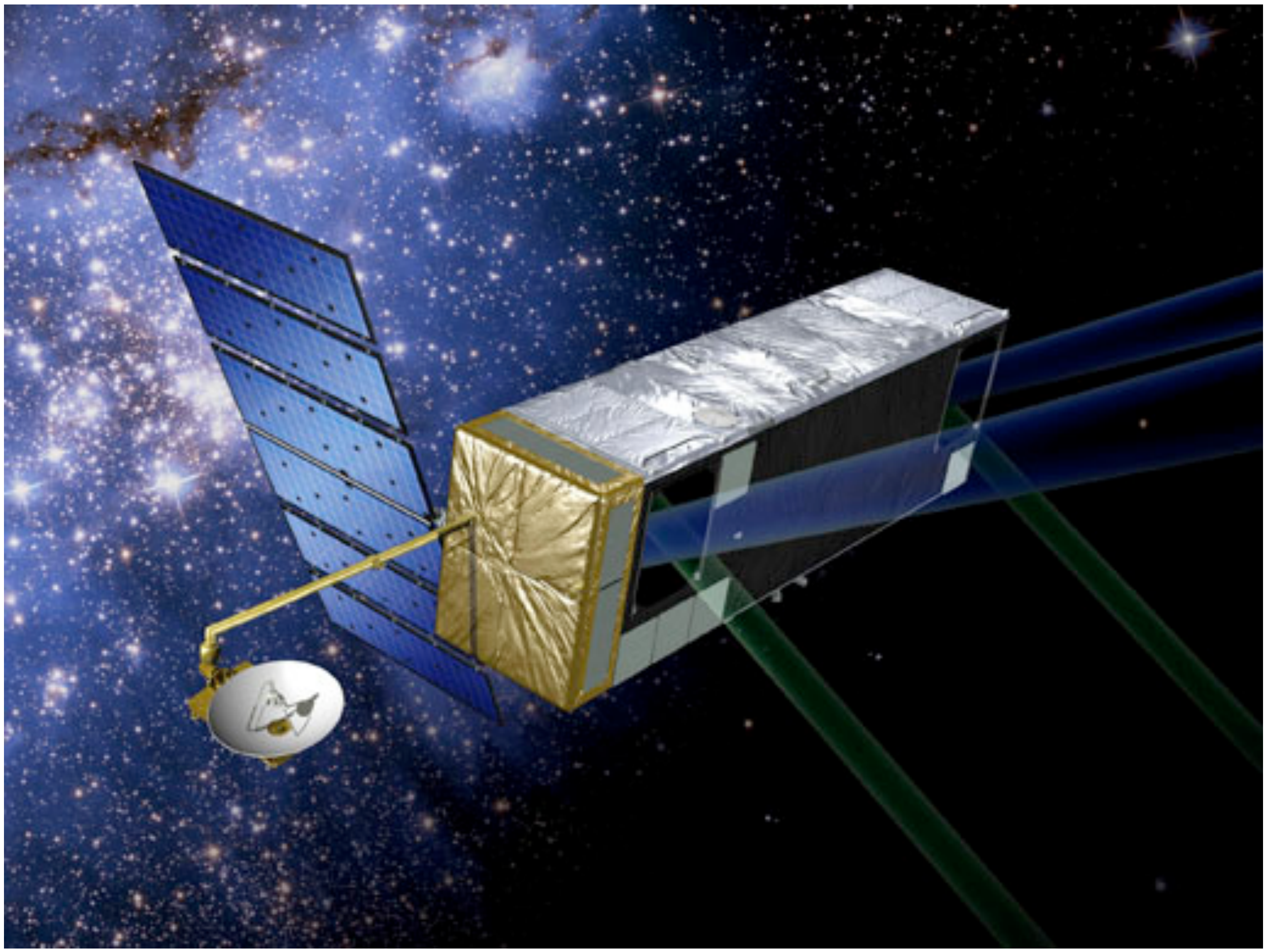


Gaia will measure
absolute angular positions
of stars and quasars to
an absolute precision
of 5-200 microarsecs,
dependent on magnitude.

Will do this for:

one billion stars
one million quasars

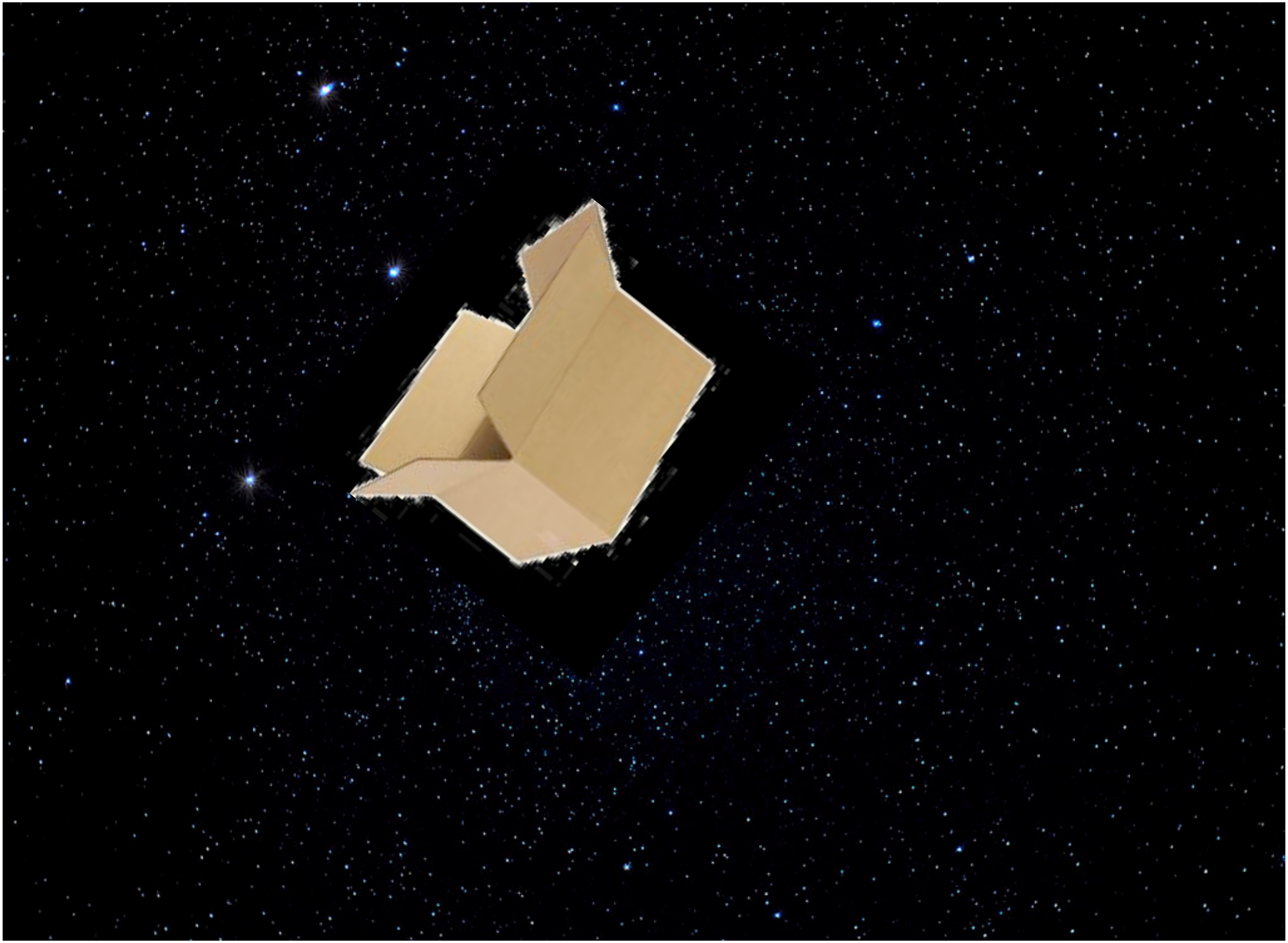


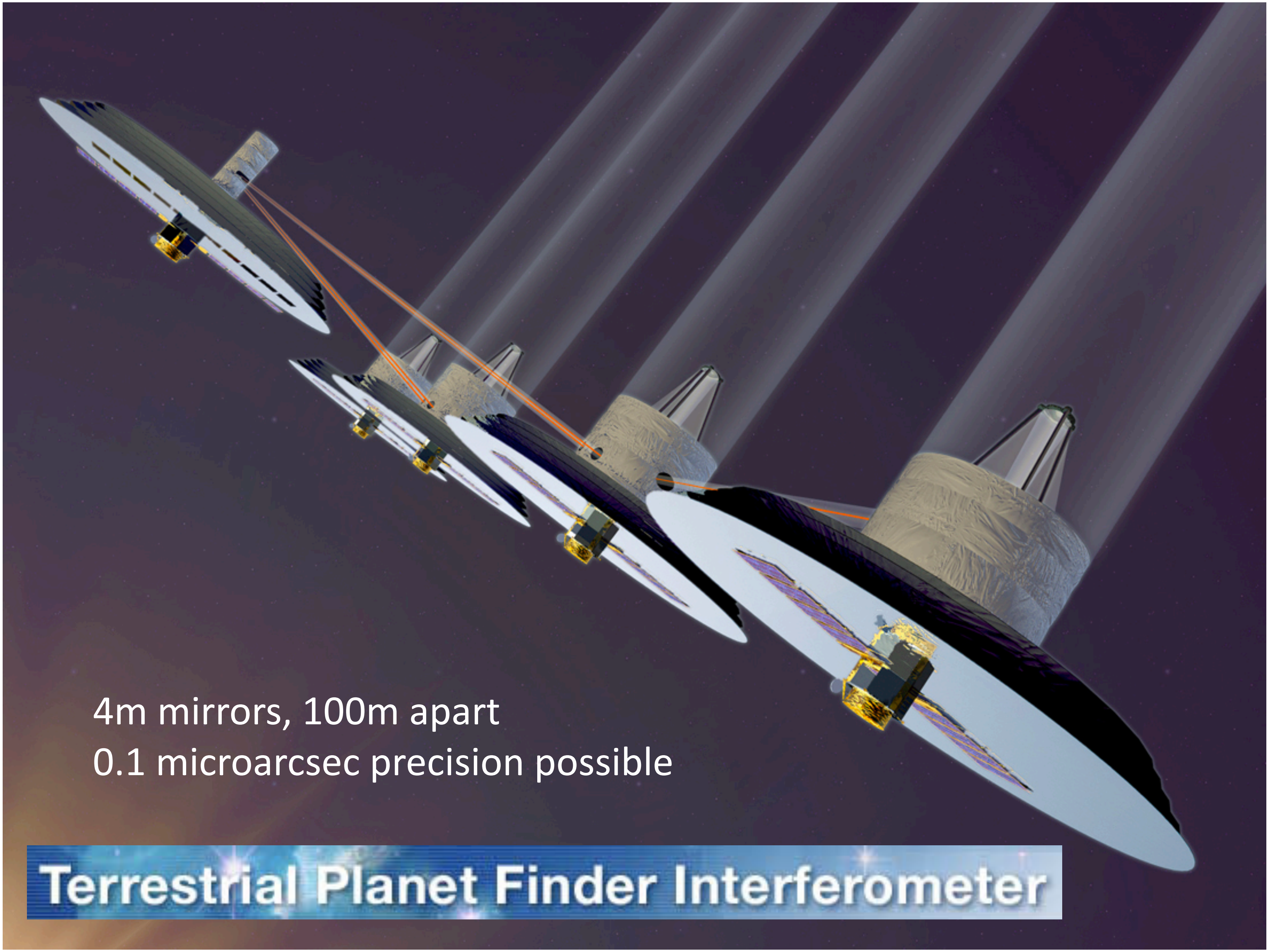


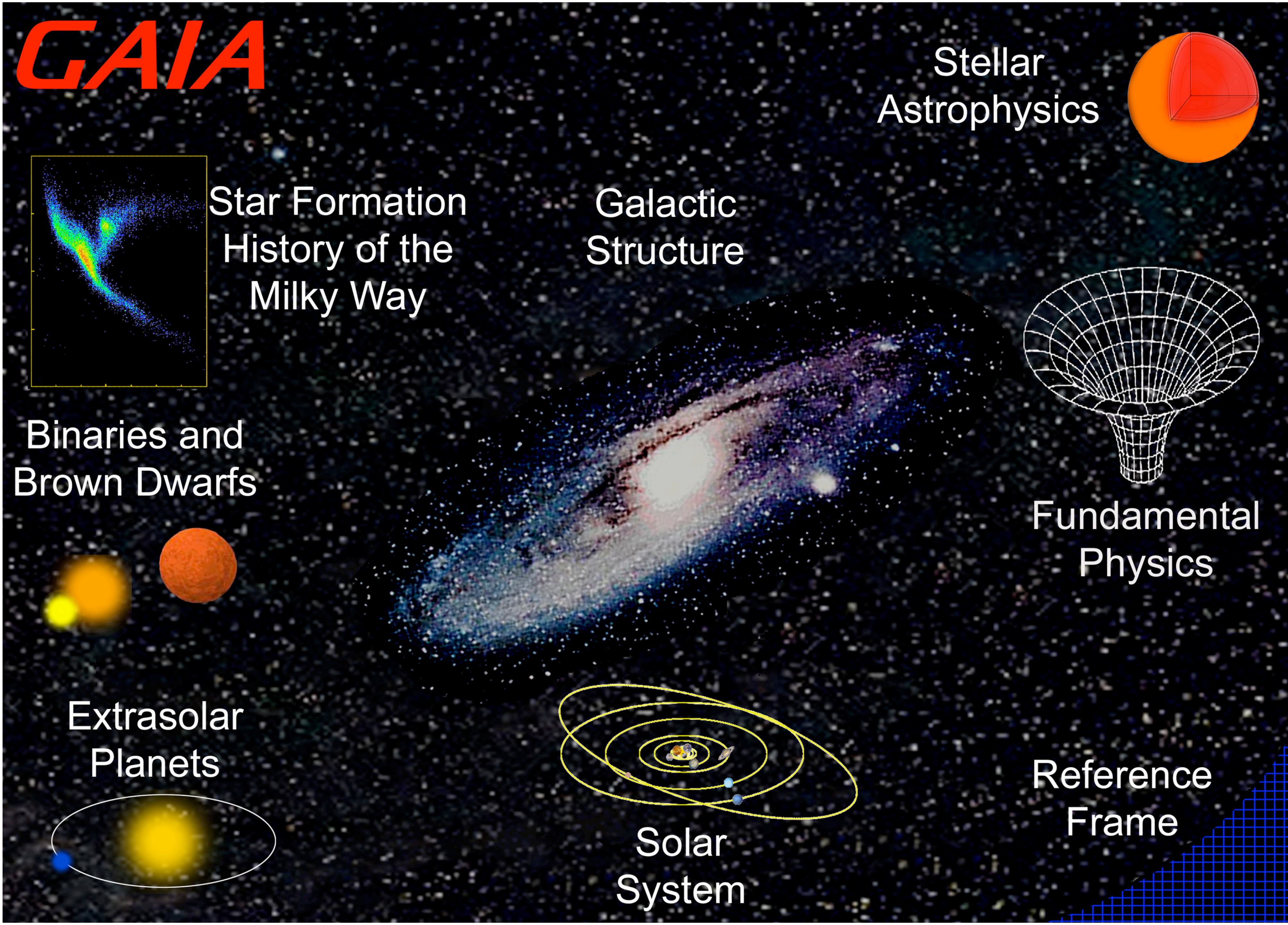
SIM will accept
observing proposals
-not a survey like GAIA

-can measure positions
with ~few
microarsec accuracy
for faint objects- just
need to integrate longer.

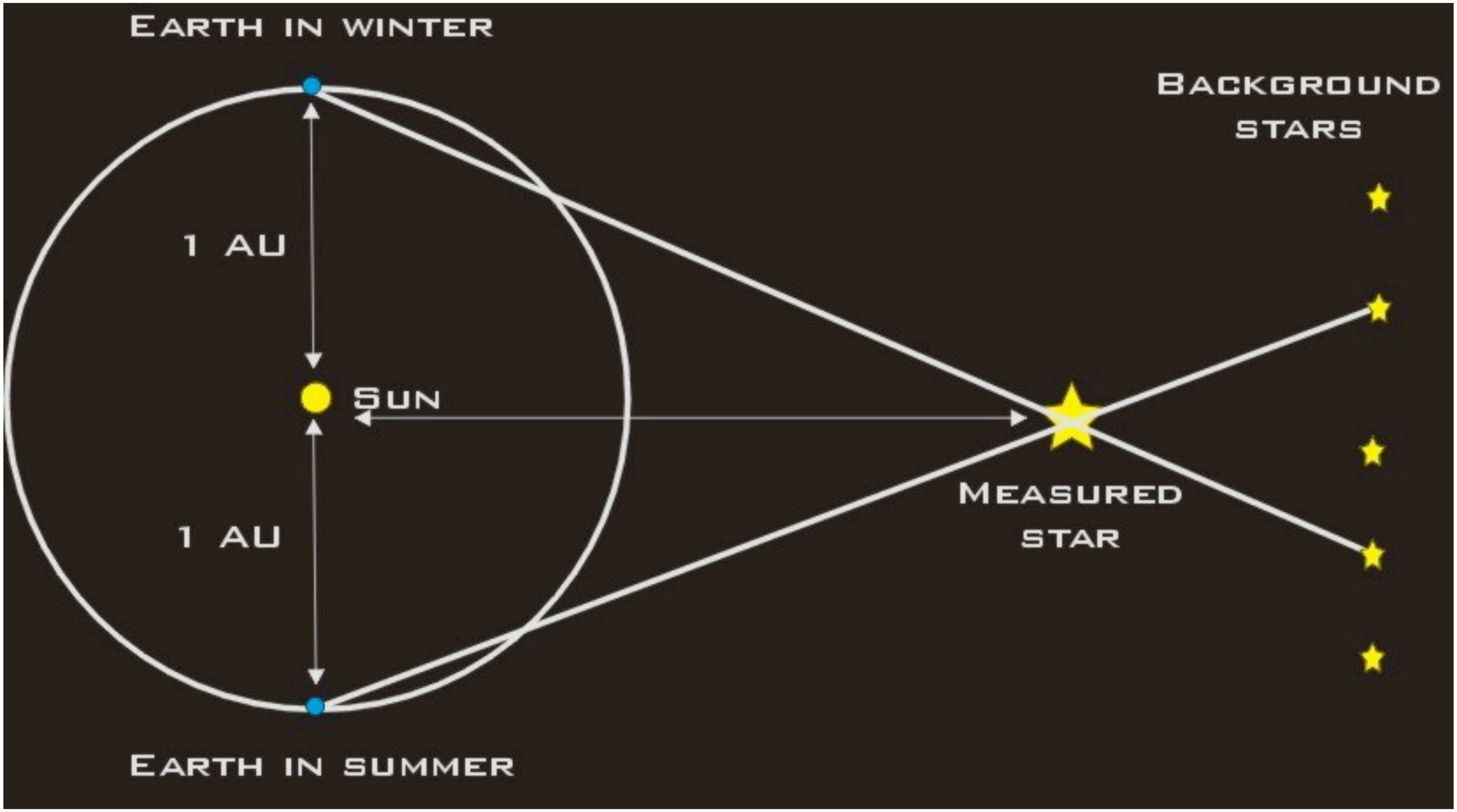
-only has 50cm mirrors



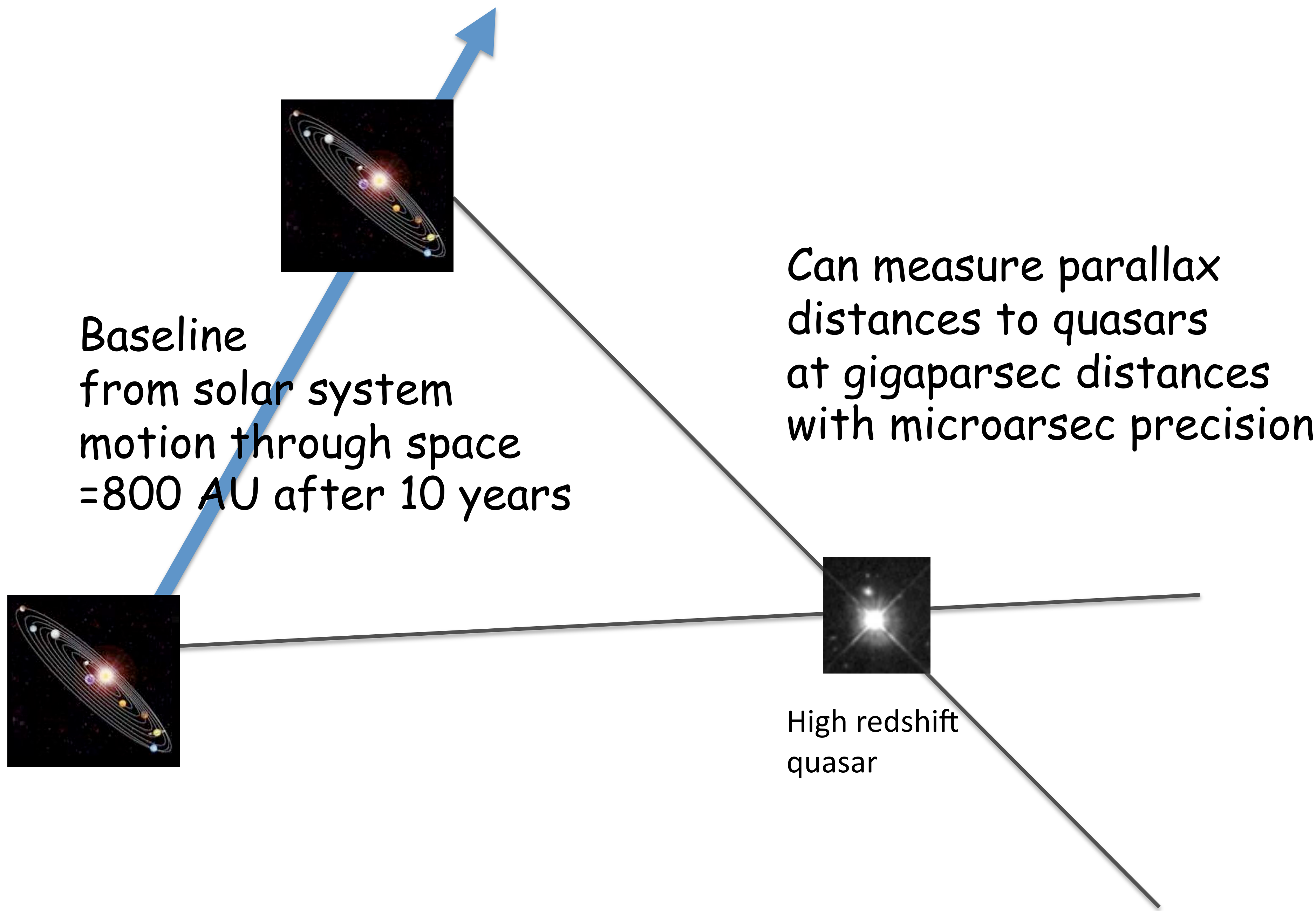

4m mirrors, 100m apart
0.1 microarcsec precision possible
Terrestrial Planet Finder Interferometer


GAIA
Stellar Astrophysics
Star Formation History of the Milky Way
Galactic Structure
Binaries and Brown Dwarfs
Fundamental Physics
Extrasolar Planets
Solar System
Reference Frame

Parallax distance



With microarsec precision, can measure parallax shift and hence distance of objects 1 megaparsec away
- not far enough for cosmology



(A new version of secular parallax)

Observable relations in relativistic cosmology.

By **W. H. McCrea.**

With 1 figure. (Received December 10, 1934.)

The assumptions underlying the formulation of the line-element of the expanding universe, and the derivation of "world-pictures" in such a universe, are recapitulated. This enables one to know what assumptions are being tested by any particular comparison with observation. Formulae are given for "distance" in an expanding universe as judged by apparent size, apparent luminosity, parallax, rigid measuring rods. Problems of spectral displacement and spectral energy distribution are discussed. The number-density of nebulae, and the information to be obtained from counts of nebulae, are studied. Application is made to the cases of MILNE's "hydrodynamic" universe, and the EINSTEIN-DE SITTER "flat" universe. Observable differences between general relativity and NEWTONIAN models are examined.

6. *Parallax.* The distance S is not in general the same as that determined by parallax. Suppose unit length δl is held at A perpendicular to AB, and let $\delta\vartheta$ be the angle between the apparent directions of B as viewed from the two ends of δl. Then the "distance" P is measured according to the usual astronomical practice by the ratio $\delta l/\delta\vartheta$.

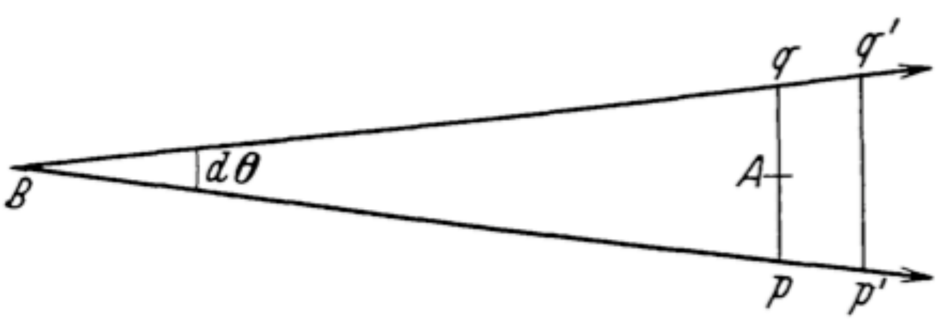


Fig. 1.

Actually this is not an important quantity for the practical study of large scale effects in the universe, since direct parallax measurements are not possible for "large" distances, but for the sake of completeness we shall find an expression for P.

Parallax distance

$$r = \begin{cases} \frac{c}{H_0}\frac{1}{\sqrt{\Omega_k}}\tanh(\frac{\sqrt{\Omega_k}H_0}{c}D) & \Omega_k > 0 \\ D & \Omega_k = 0 \\ \frac{c}{H_0}\frac{1}{\sqrt{|\Omega_k|}}\tan(\frac{\sqrt{|\Omega_k|}H_0}{c}D) & \Omega_k < 0 \end{cases},$$

where

$$D = c\int_0^z \frac{dz'}{H(z)}.$$

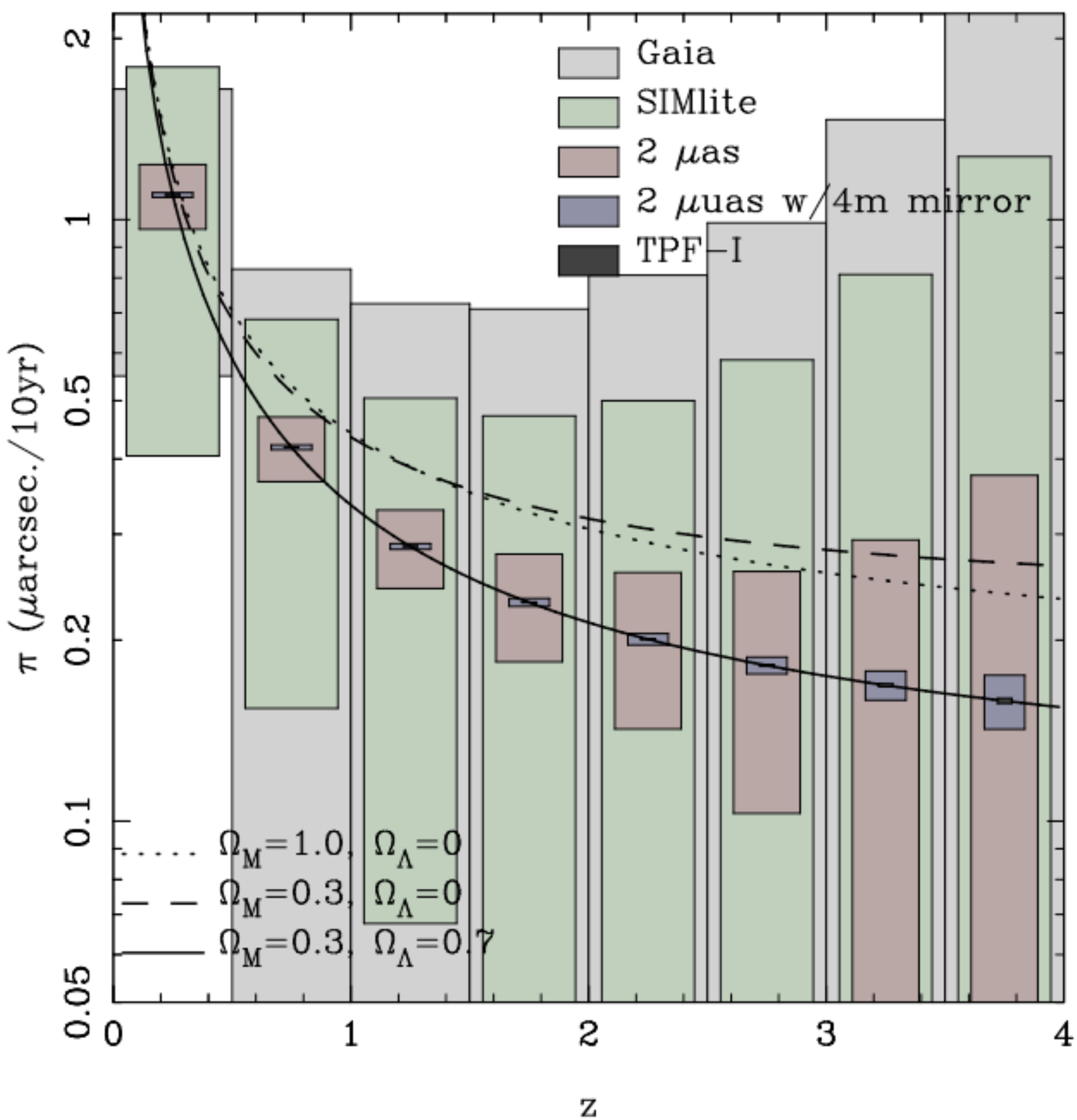
Compare to luminosity distance and ang. diam. distance:

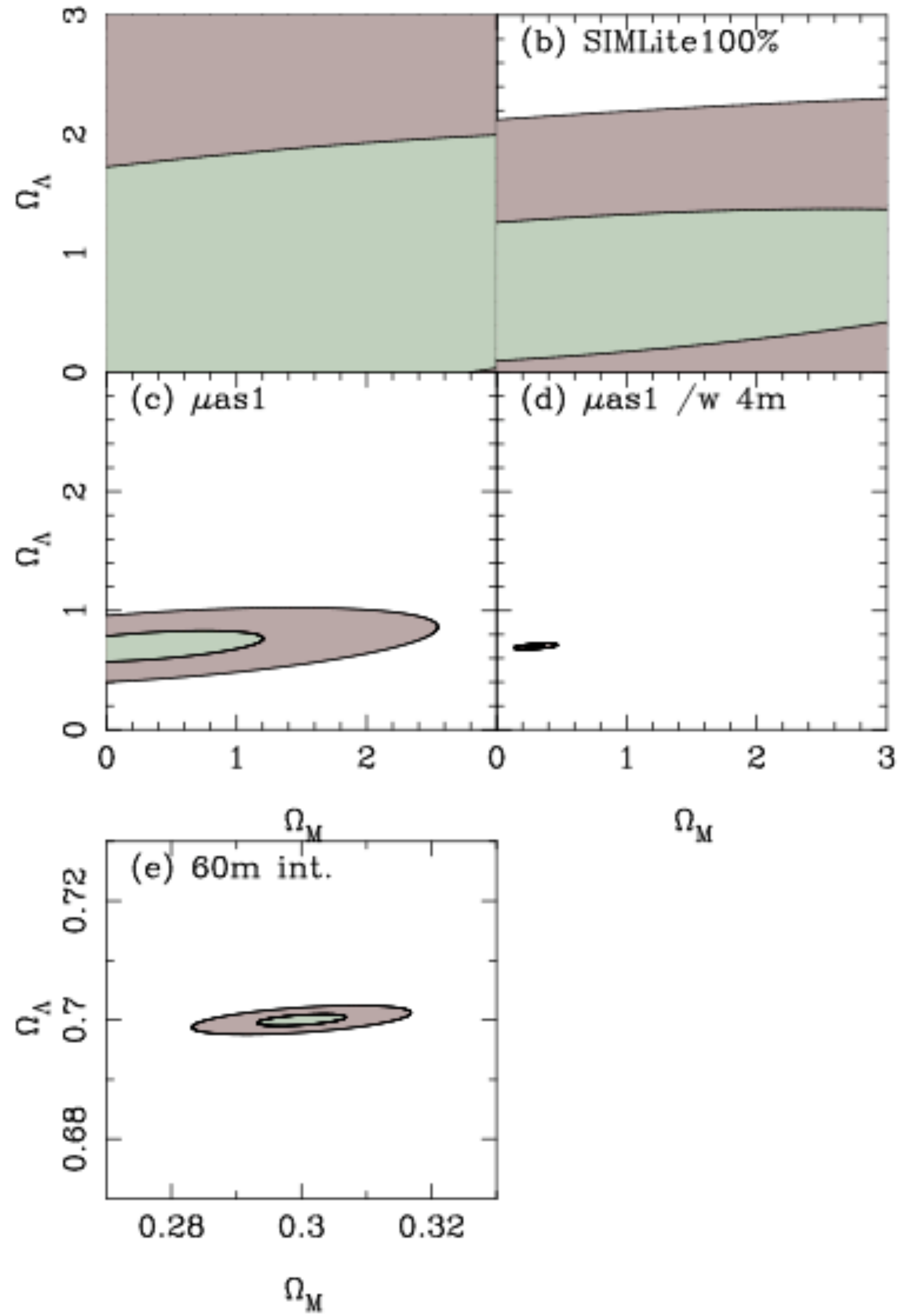
$$D_{\rm L} = (1+z)\, D_{\rm M} = (1+z)^2\, D_{\rm A}$$

$$D_{\rm M} = \begin{cases} D_{\rm H}\,\frac{1}{\sqrt{\Omega_k}}\,\sinh\left[\sqrt{\Omega_k}\,D_{\rm C}/D_{\rm H}\right] & \text{for } \Omega_k > 0 \\ D_{\rm C} & \text{for } \Omega_k = 0 \\ D_{\rm H}\,\frac{1}{\sqrt{|\Omega_k|}}\,\sin\left[\sqrt{|\Omega_k|}\,D_{\rm C}/D_{\rm H}\right] & \text{for } \Omega_k < 0 \end{cases}$$

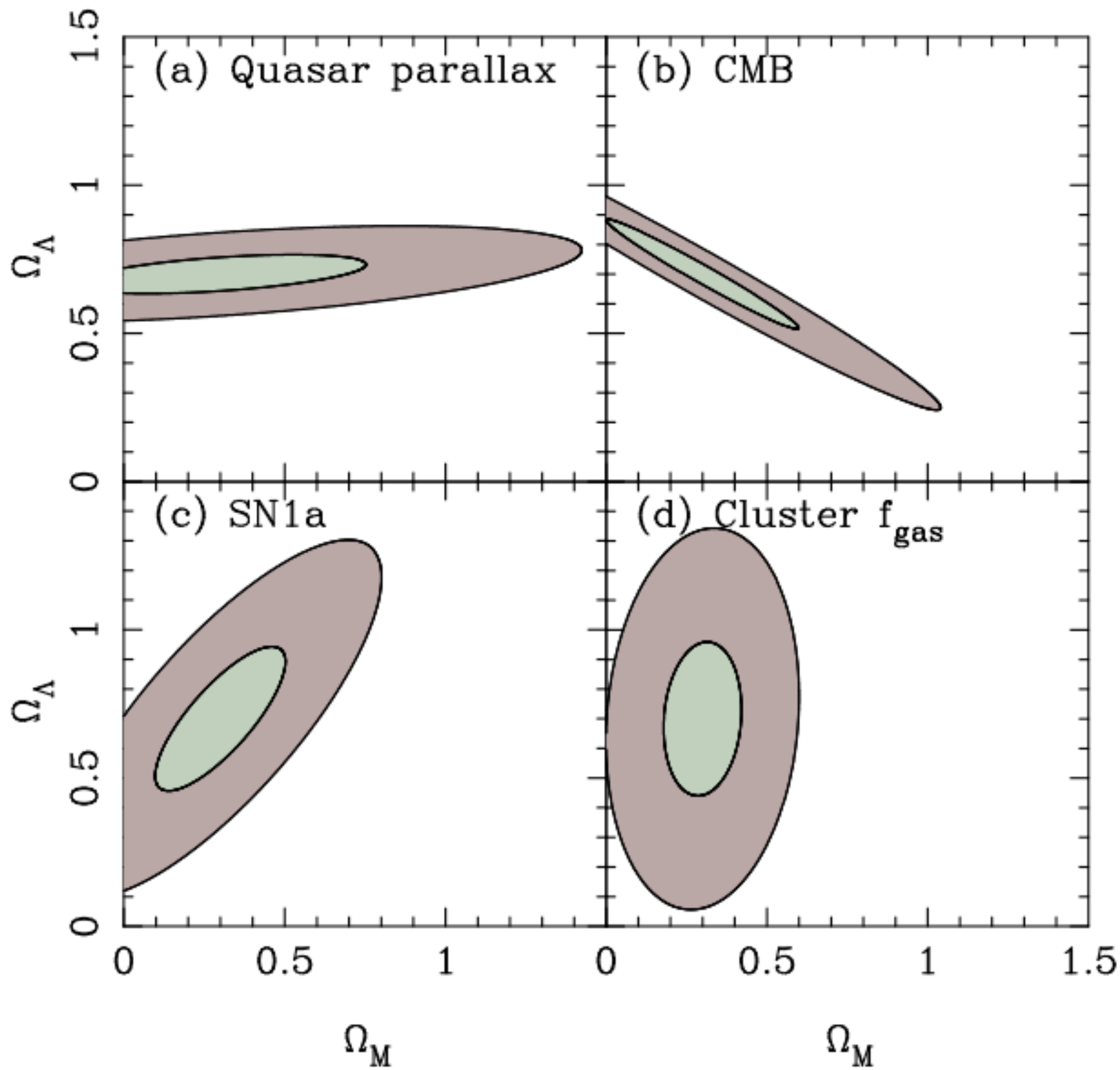
Average
over parallax
measurements
of quasars in
redshift bins

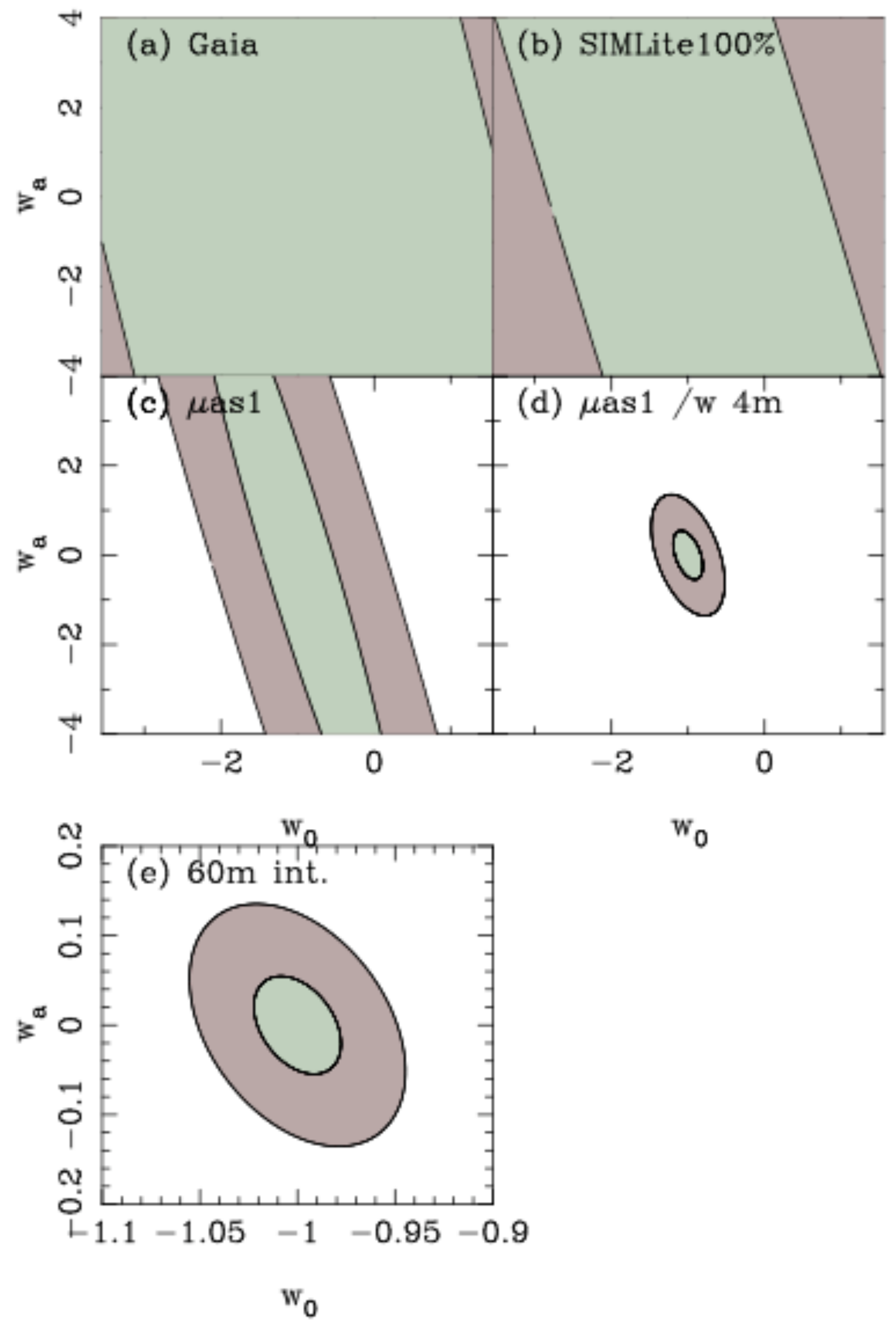
(Error bars
Poisson only)





(b) SIMLite100%
(c) μas1
(d) μas1 /w 4m
(e) 60m int.
Ω_Λ
Ω_M
0
1
2
3
0.68
0.7
0.72
0.28
0.3
0.32


(a) Quasar parallax
(b) CMB
(c) SN1a
(d) Cluster f_{gas}
Ω_Λ
Ω_M
0
0.5
1
1.5


(a) Gaia
(b) SIMLite100%
(c) μas1
(d) μas1 /w 4m
(e) 60m int.
w_a
w_0
4
2
0
−2
−4
0.2
0.1
−0.1
−0.2
−1.1
−1.05
−1
−0.95
−0.9

Systematic and statistical errors:

Systematic errors (could mimic all sky parallax Shift):

(a) Aberration due to galactocentric acceleration

(can be subtracted + has no redshift dependence)

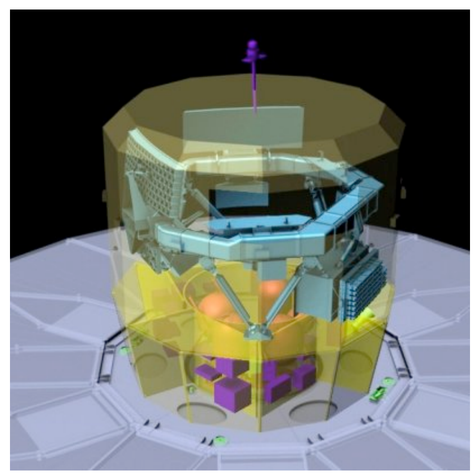
Statistical and systematic errors.

Statistical errors

(a) Measurement errors- related to angular precision of measurement:

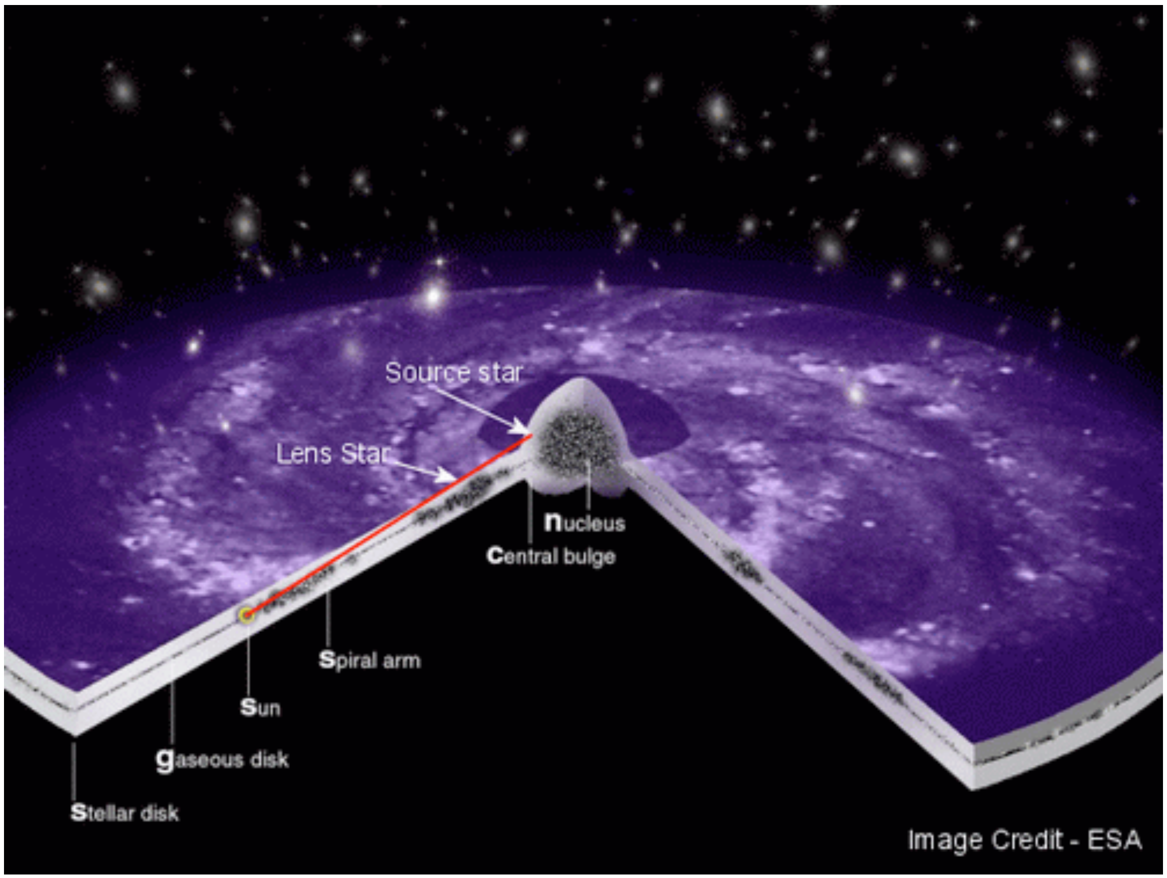
V mag	6-13	14	15	16	17	18	19	20
$\sigma_{\rm PM}$ (μas yr^{-1})	5	7	11	18	30	50	80	145

Table 2. Sky-averaged rms proper motion error as a function of visual apparent magnitude for the Gaia satellite (data from Lindegren et al. 2008, see §3)



Statistical errors.

(b) Weak microlensing:



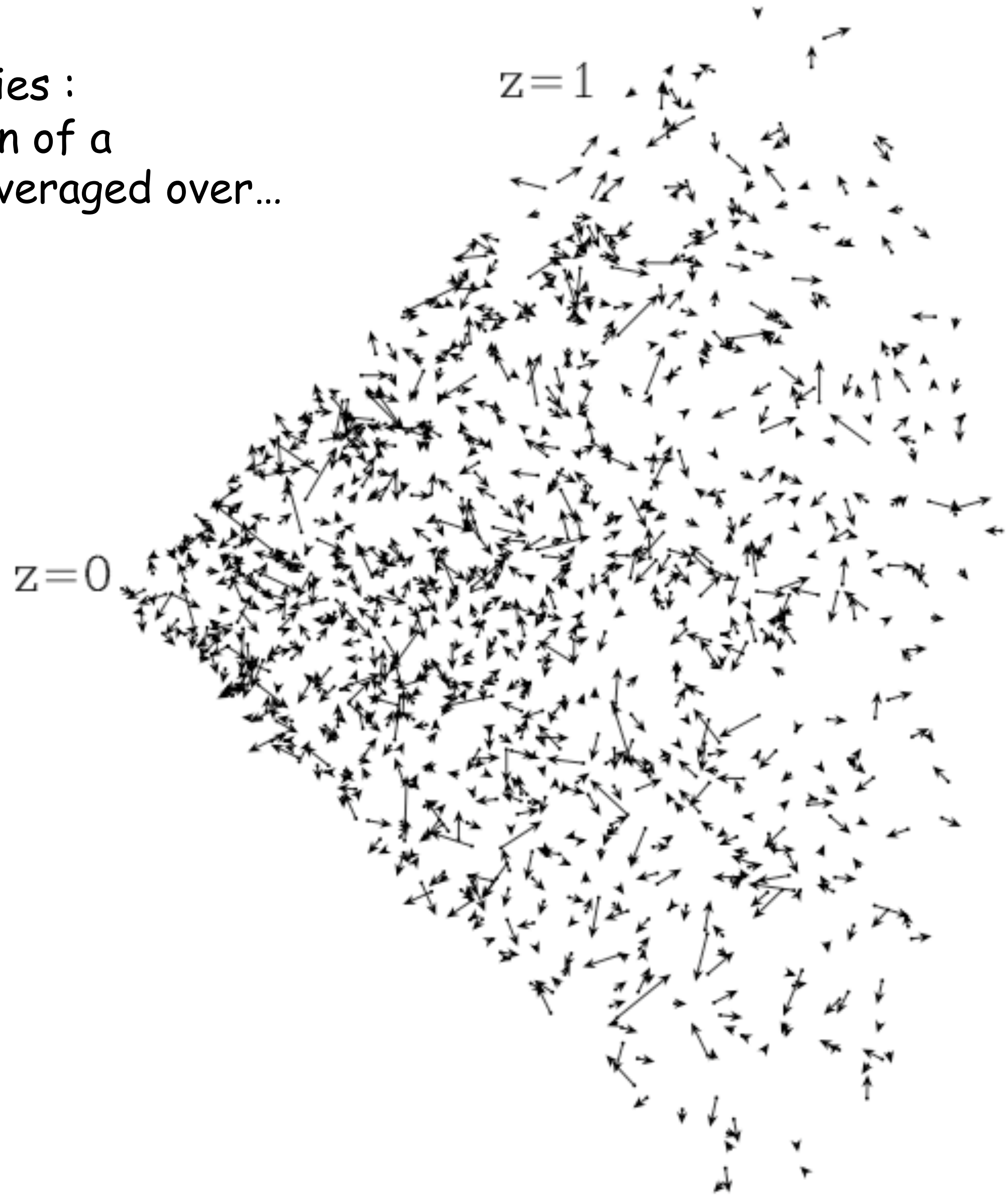
Will cause
random image
motions
of up to
0.1 microarcsec

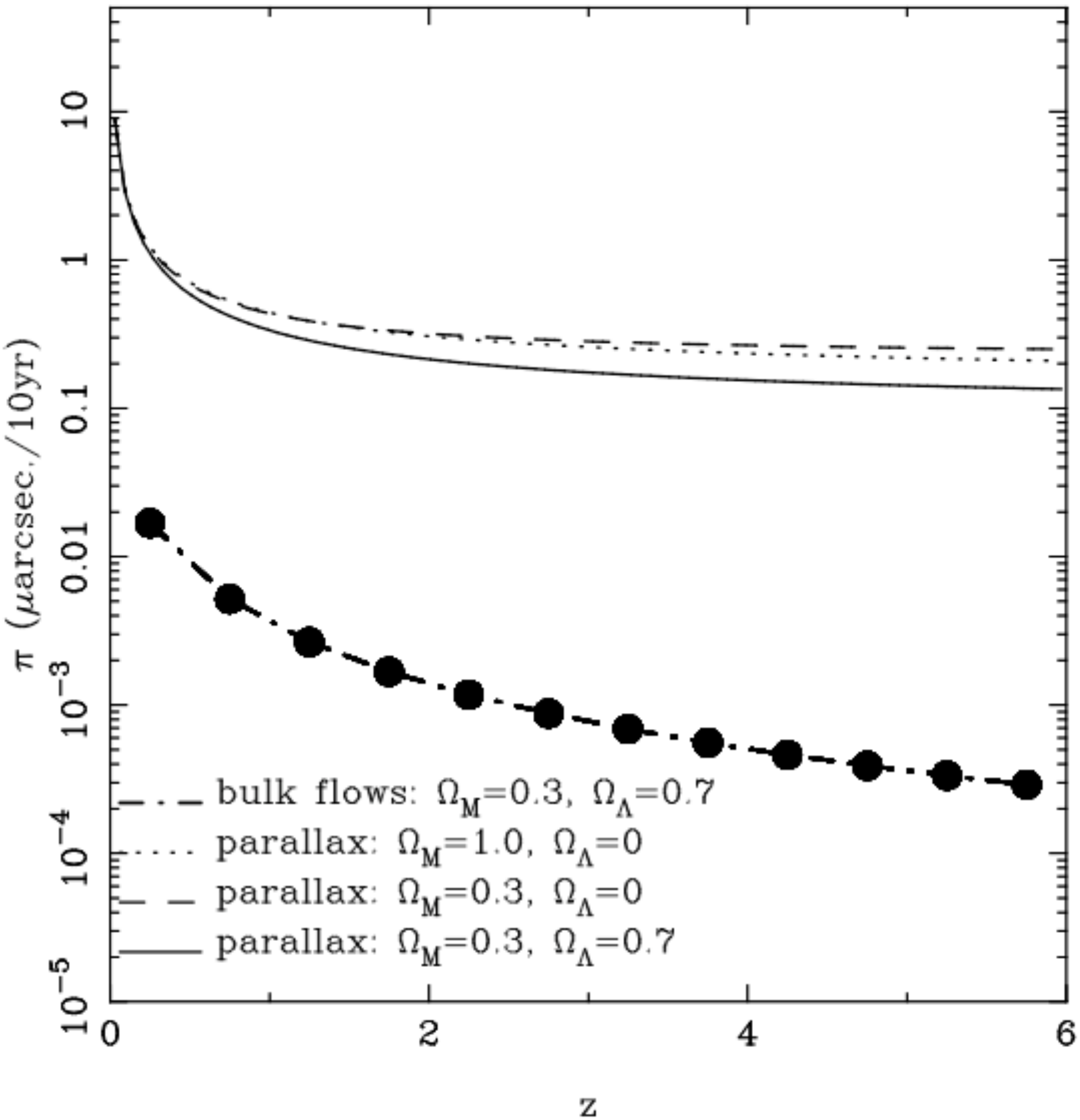
Statistical errors:

(c) Image centroiding of variable source (quasar) on top of galaxy makes image centroid wander: fraction of microarcsec.

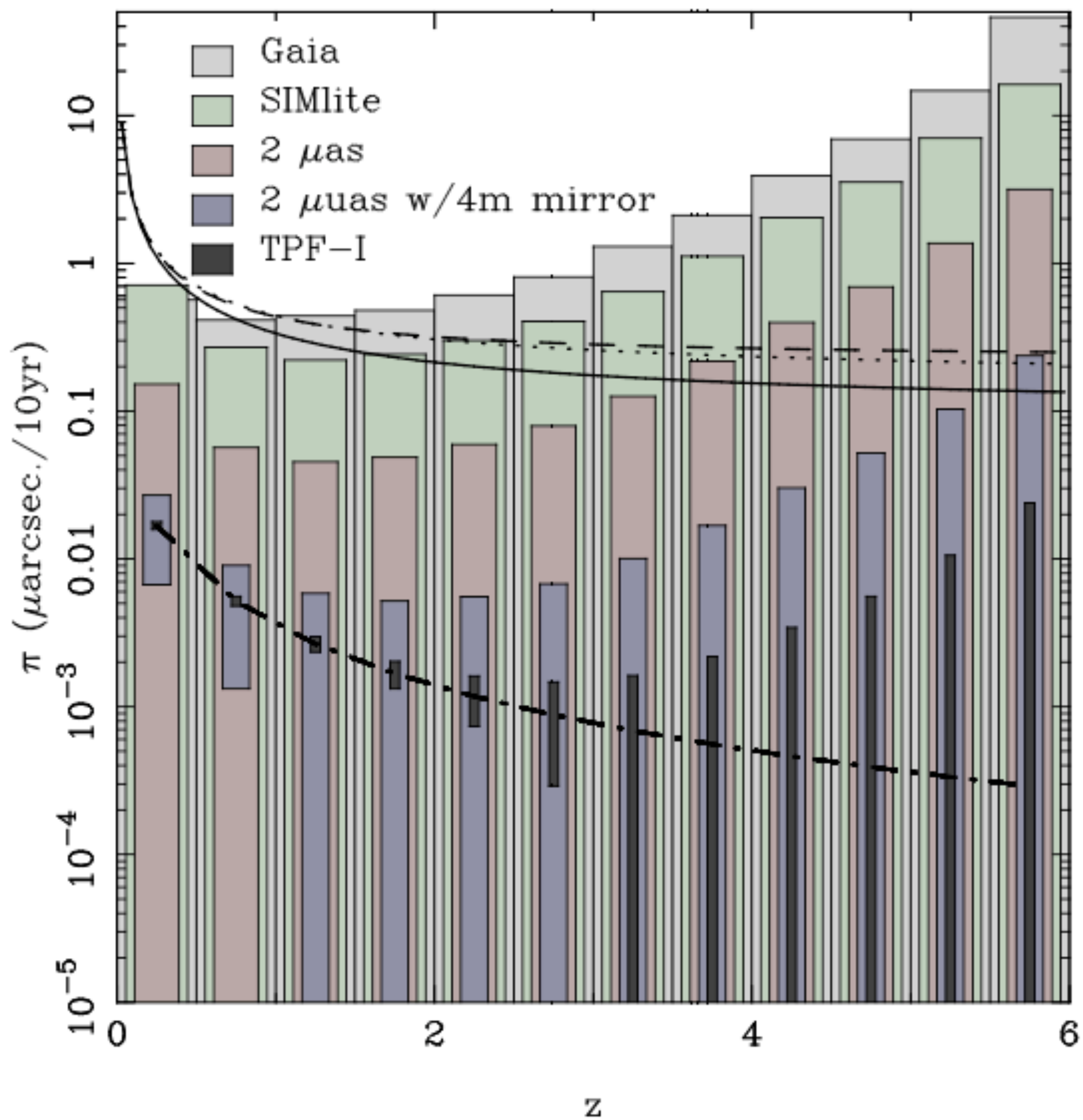
Statistical errors:

(d) Quasar peculiar velocities :
Individually up to a fraction of a
microarcsec – but can be averaged over…





bulk flows: Ω_M=0.3, Ω_Λ=0.7
parallax: Ω_M=1.0, Ω_Λ=0
parallax: Ω_M=0.3, Ω_Λ=0
parallax: Ω_M=0.3, Ω_Λ=0.7
π (μarcsec./10yr)
z

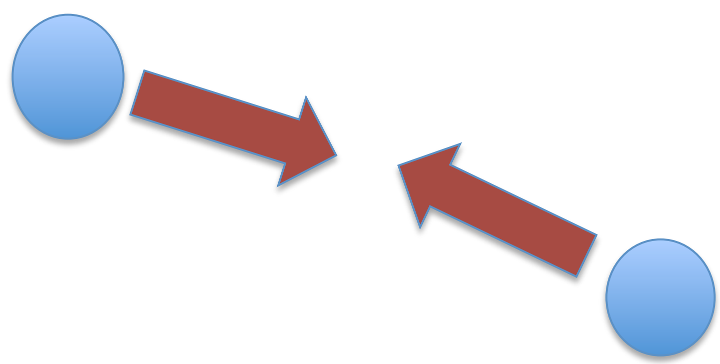


Gaia
SIMlite
2 μas
2 μuas w/4m mirror
TPF−I
π (μarcsec./10yr)
10
1
0.1
0.01
10−3
10−4
10−5
0
2
4
6
z

Bulk flows on very large scales are too difficult to measure with Gaia and SIM …

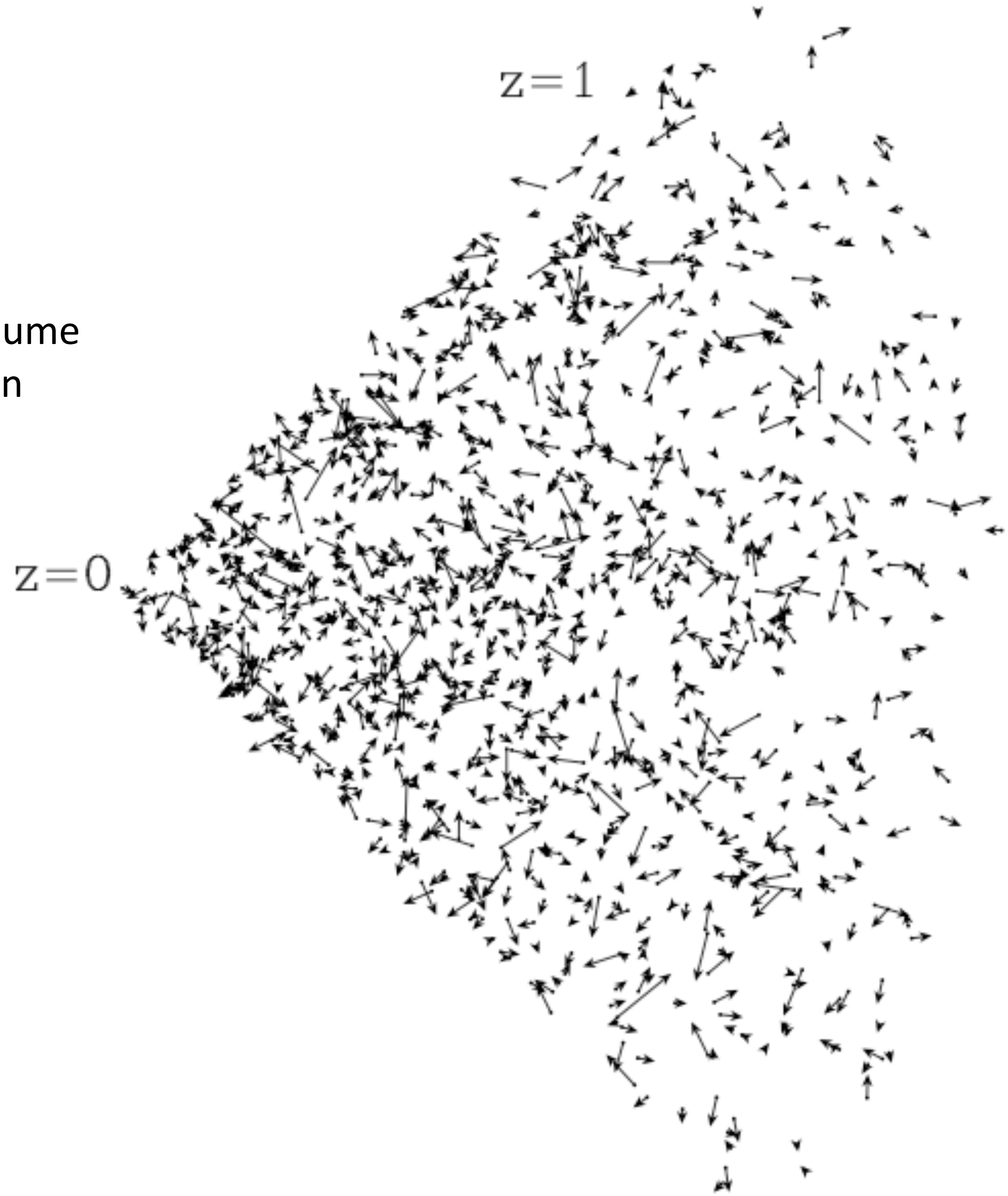
… is there an easier proper motion statistic to measure?

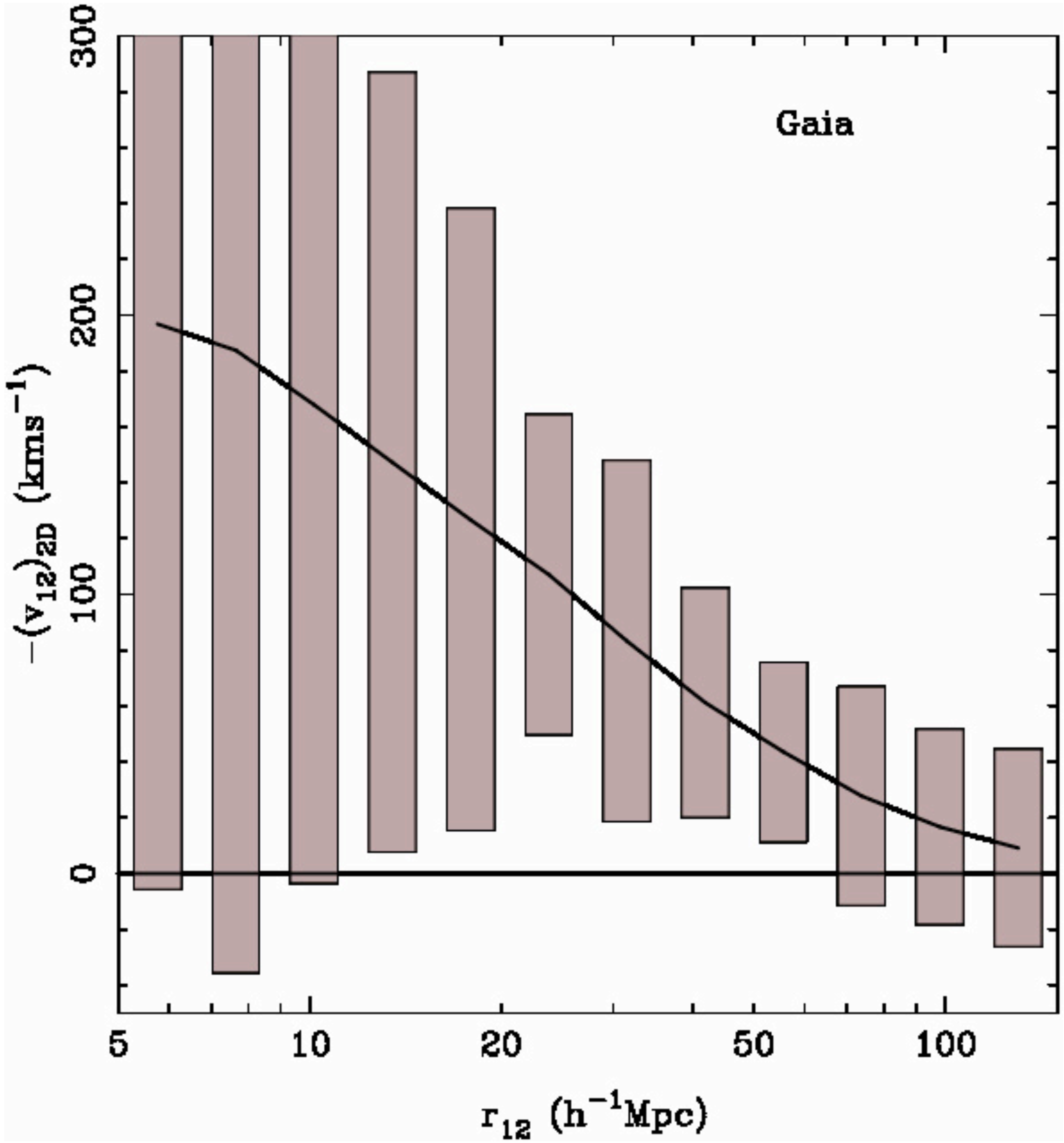
Yes! quasar pairwise motions v_{12}



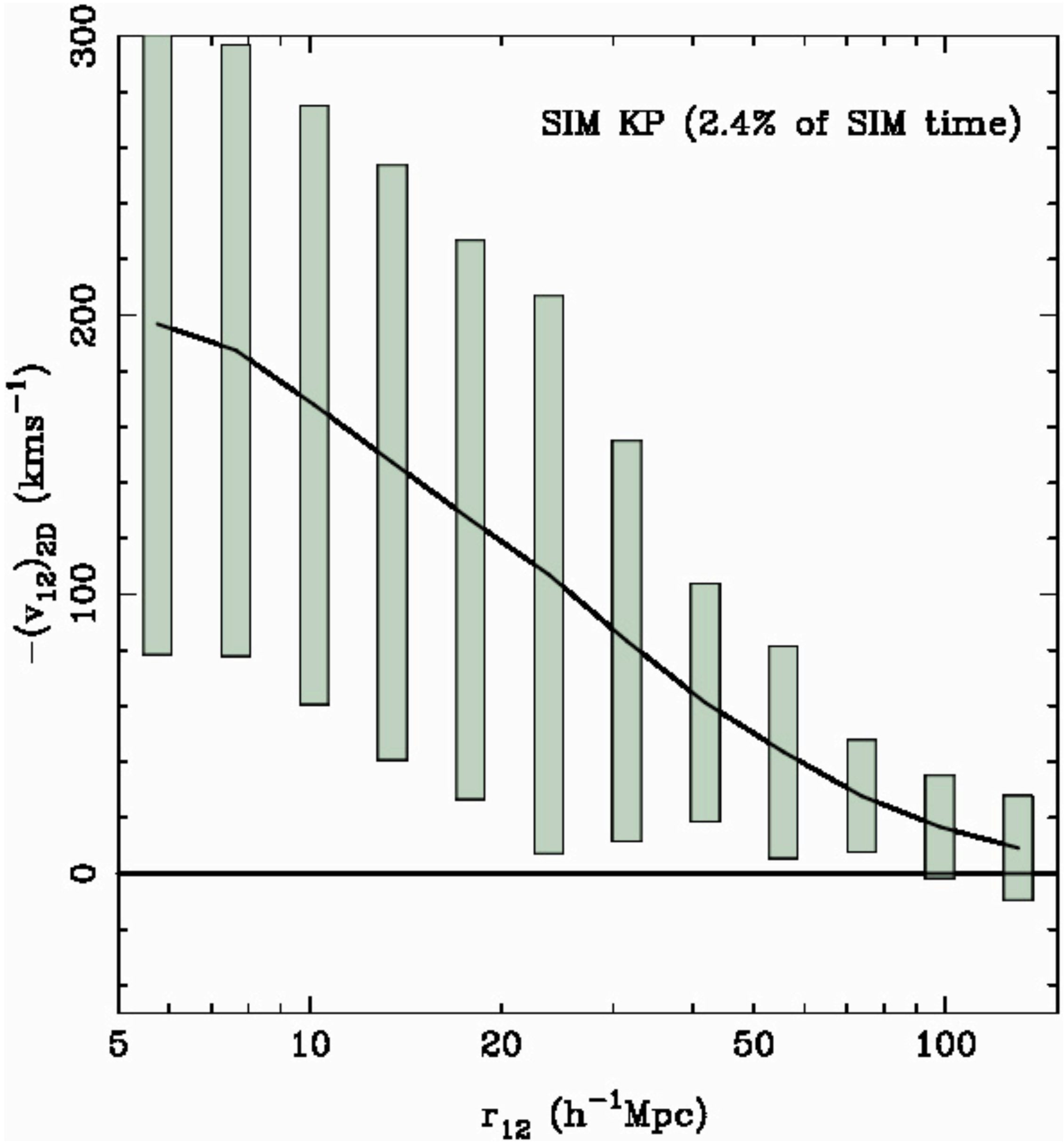
Predictions:

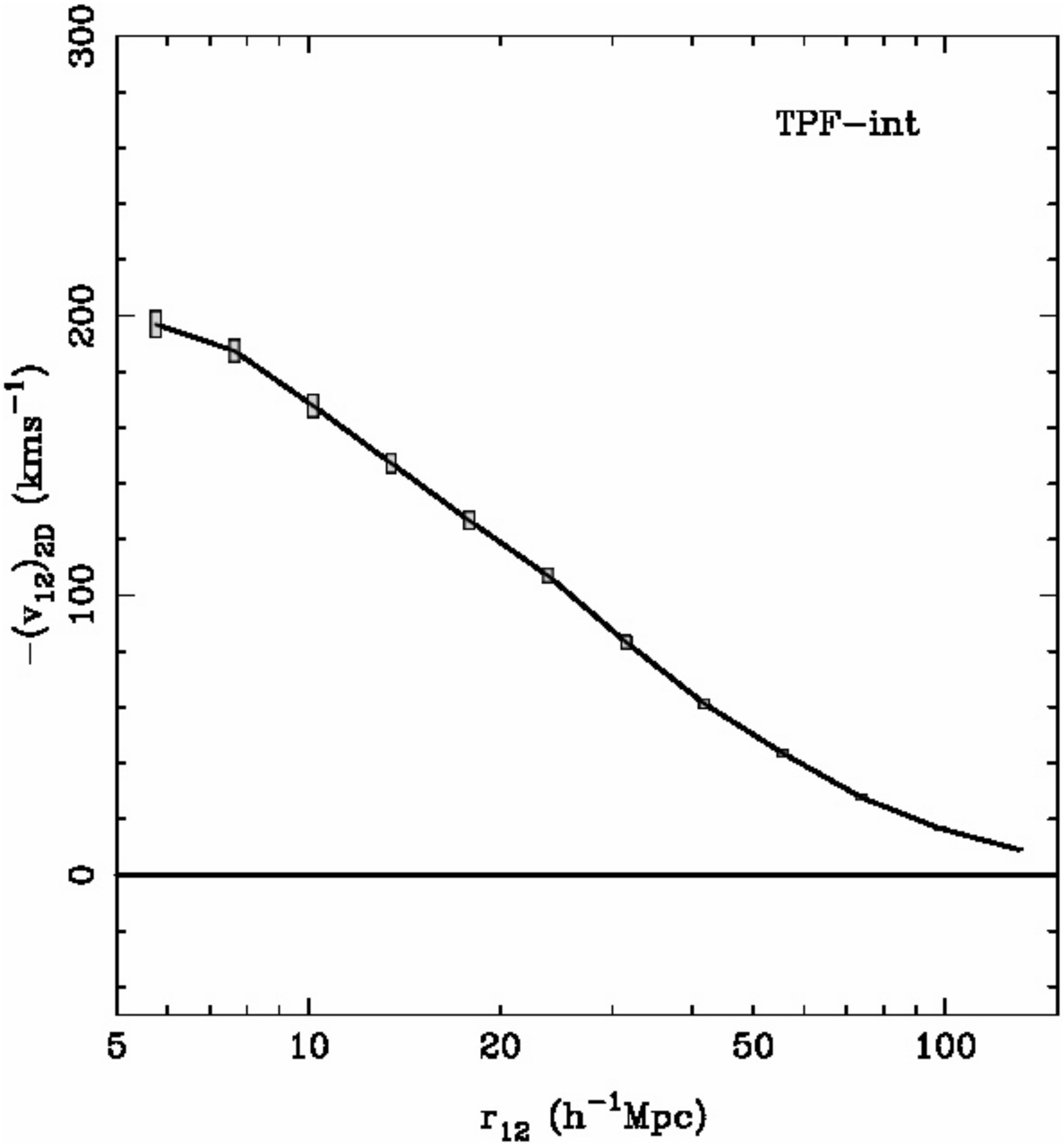
use Hubble volume
CDM simulation





Including covariances between bins, Gaia could make
a 4.5 sigma detection of quasar proper motions (at mean z~1)


SIM KP (2.4% of SIM time)
300
200
100
0
$-(v_{12})_{2D}$ (kms^{-1})
5
10
20
50
100
r_{12} (h^{-1}Mpc)


TPF−int
300
200
100
0
$-(v_{12})_{2D}$ (kms^{-1})
5
10
20
50
100
r_{12} (h^{-1}Mpc)

Finally, what about the Hubble constant?

There are 921 AGN in the Veron catalog
within 100 Mpc

Many have nuclear magnitude 14.5 magnitude in V

-> from SIM time calculator, a SIM KP
(2.4% of SIM total observing time) could measure
position with accuracy 5.75 muas.

-> 0.18 muas for 921 AGN vs 20 muas parallax
shift over 10 years

H_0 to 1%

Other real time cosmology: redshift drift.

THE CODEX-ESPRESSO EXPERIMENT: COSMIC DYNAMICS, FUNDAMENTAL PHYSICS, PLANETS AND MUCH MORE...

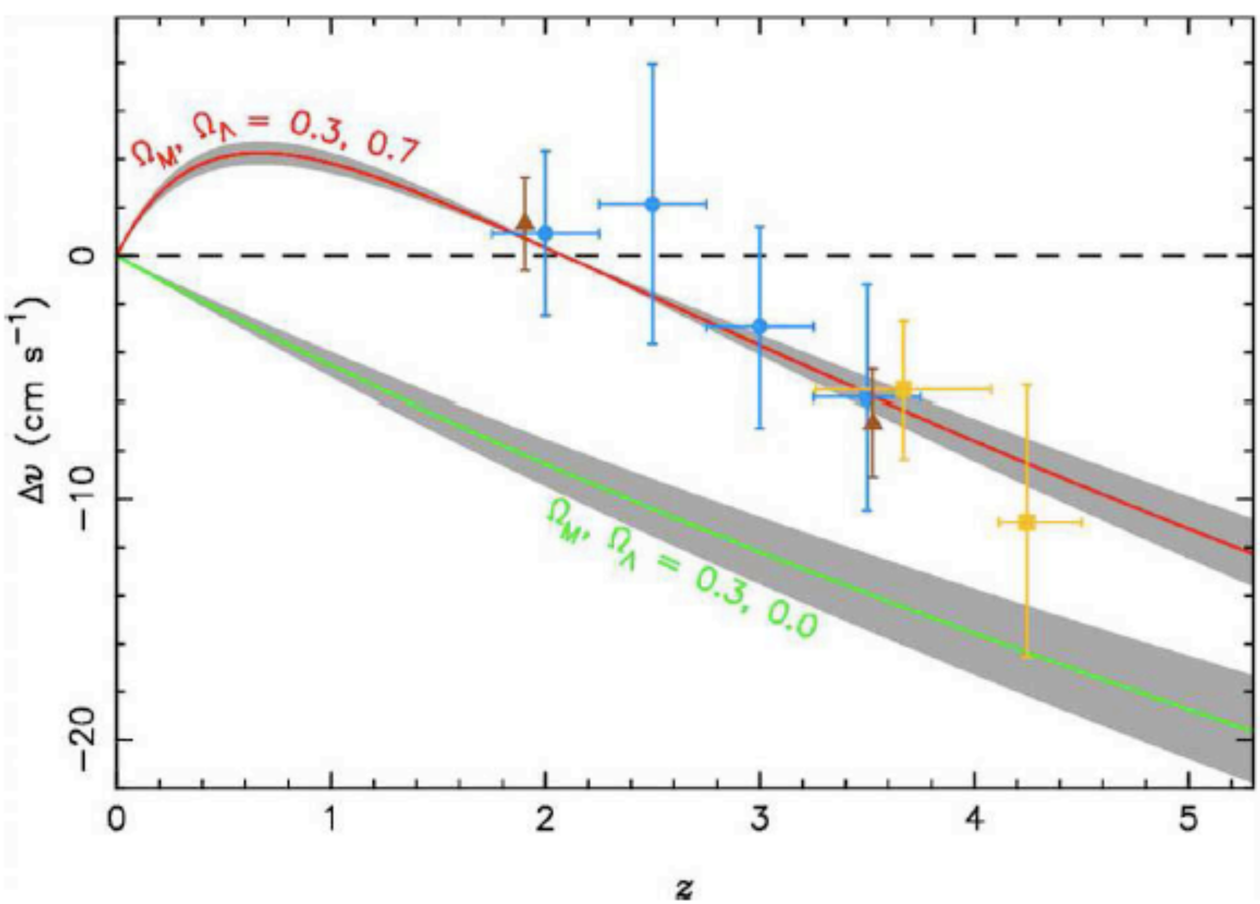


Fig. 3. – CODEX observing strategy assuming 2.2 nights/month of observation with a 42m ELT over 15 years. The three different sets of data points represent different implementations of the redshift drift experiment, each being optimal for a different goal: Blue points: 20 targets (in 4 bins), selected to give the highest overall radial velocity accuracy (2.13 cm/s). Yellow points: 10 targets selected to give the largest possible significance of a non-zero detection. Brown points: 2 targets, selected to give the best constraints on the acceleration and dark energy. The grey shaded areas around the curves correspond to the present H_o uncertainty of $+/-8$ km/s/Mpc.

Conclusions:

Astrometric cosmology will be feasible:

GAIA should detect quasar parallax at the >3 sigma level

SIM may be able measure the Hubble constant to 1% precision

TPF-I will be able to rival "Stage IV" dark energy missions like JDEM and SNAP

+ measure quasar proper motions – another new probe of cosmology.

The far future:

NASA Planet Imager :

5x8m space telescopes 6000 km apart